

## **Plasma sheet electromagnetic power generation and its dissipation along auroral field lines.**

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**Abstract.** During a fortuitous meridional conjunction of POLAR and Geotail at the nightside magnetosphere throughout the course of a geomagnetic substorm, measurements of Poynting flux indicate that most of the electromagnetic energy flux density radiated in the form of waves at the location of Geotail at  $\sim 18R_E$  is dissipated before it reaches POLAR at  $\sim 5R_E$ , i.e., above the auroral acceleration region. While the Poynting flux measured at POLAR (and to a greater extent at Geotail) is more than sufficient to account for particle acceleration below the satellite, it still represents a small portion of the Earthward-directed particle energy flux density measured at Geotail. If even a small portion of the bursty bulk flow energy couples to Alfvén waves it would be energetically sufficient to account for the expected auroral energy deposition during substorms. Power dissipation via kinetic Alfvén waves along auroral field lines represents a viable mechanism by which localized reconnection flows can slow down. This may explain why fast Earthward flows reported at mid-tail ( $>30 R_E$ ) distances can exist with no near-Earth counterpart, and why any putative candidates of an ionospherically reflected flow burst pulse in the tail have very small amplitudes.

## **1. INTRODUCTION**

Recent work (Wygant et al., 2000) suggests that the Poynting flux on auroral field lines at altitudes 4-6  $R_E$  measured by the POLAR satellite is at least factor of 10 larger than expected from measurements of the same quantity at subauroral altitudes. Since the measured electromagnetic energy flux is comparable to the expected particle energy flux in the auroral region, it was surmised that most of the observed electromagnetic energy is actually deposited in the particles within the acceleration region. Such waves represent a significant energy inflow to the auroral ionosphere. The energy source for those waves is expected to be in the tail plasma sheet, at or Earthward of, the neutral line.

Bursty bulk flows (BBFs) represent a significant energy transport towards Earth (Angelopoulos et al., 1994). Such flows measured on the AMPTE/IRM satellite, with apogee at  $\sim 19R_E$ , correlate statistically with AL decreases (Angelopoulos, 1996), suggesting that they are an integral part of substorm activity. Exactly how, or even how much of this energy gets deposited to the ionosphere is not clear. When studied on a case-by-case basis from close enough to Earth, such flows are indistinguishable from the current disruption process (Angelopoulos et al., 1999), occurring no more than 1 minute prior to the earliest substorm onset indicator (e.g., Angelopoulos et al., 1996a). Much work has been devoted to the formation of the current wedge at the interaction of the colliding bursty flow jet with the Earth's dipole (Shiokawa et al., 1997, Shiokawa et al., 1998, Birn et al., 1999). On fortuitous occasions when multiple magnetospheric and auroral observations were possible during the recovery phase of substorms, fast flow bursts from the near-Earth tail have been timed to correlate well with geosynchronous injections and simultaneous rapid equatorward motion of auroral luminosity, otherwise known as north-south forms (Henderson et al., 1998, Sergeev et al., 1999). Such flows can originate as far as  $40 R_E$  from Earth and penetrate through an already dipolarized plasma sheet (Sergeev et al., 2000).

However, fast flows also exist at mid-tail distances ( $>30 R_E$ ) in the absence of substorms. Early reports of such mid-tail flows in the absence of AE activity (Coroniti et al., 1979; 1980) came from IMP 7. In those cases plasma heating but no dipolarization or fast flows were seen in the near-Earth environment. A more recent fortuitous Geotail-WIND conjunction (Oieroset et al., 2000) confirmed that such flows can exist in the mid-tail but not make it in the near-Earth environment, which agrees with the fact that they are not very geoeffective. Such mid-tail flows have been linked to high latitude activations (Lyons et al., 1999, Zesta et al., 2000). Those activations occasionally protrude to lower latitudes and in this sense resemble the north-south arcs, or streamers. When such streamers are initiated at the poleward boundary after the previous development of a "double auroral oval" then a new substorm may erupt at the equatorward boundary (Elphinstone et al., 1995).

It is evident that from the point of view of their ionospheric response, at least three types of bursty bulk flows are present: Those that are related to the substorm expansion (pseudobreakups included), those that are related to late substorm recovery (north-south arcs) and those that are related to high latitude activations. But from the point of view of local magnetotail flow observations the three types are indistinguishable. Since the occurrence frequency of fast flows increases with distance from Earth (e.g., Baumjohann et al., 1990; Angelopoulos et al., 1994) the mid-tail flows are interesting being so frequent. In particular the question arises, where do such flows deposit their (significant) Earthward-directed energy. However, the study of any type of fast flow and its energy dissipation is interesting since, being so similar to other types, it can provide useful information on energy dissipation of any fast magnetotail flows.

A broadband spectrum of low frequency (0.1-10 min.) oscillations is present in the flow and electric and magnetic field data. Sanchez et al. (1997) using a large array of ground and space observatories showed that some of the flow periodicity is due to global mode oscillations, while Kepko and Kivelson (1999) noted that the observed flow bursty periodicity matches simultaneous Pi2 pulsation peaks. Occasionally reverse flows are seen a few minutes after an impulsive earthward flow onset, indicating possible ionospheric reflection (e.g., Angelopoulos et al., 1996a, Figure 12;

Angelopoulos et al., 1999, Figures 3 and 4). The occurrence of such tailward flows in the presence of a northward magnetic field has been pointed out more recently by Baumjohann et al., (2001). Since the nightside ionospheric conductivity is large an ionospherically reflected pulse is expected to be quite large. In fact, Nishida (1979) attempting to explain the presence of tailward flows in the near-Earth tail showed that the ionospherically reflected pulse can be comparable in magnitude and opposite in direction to the incident pulse. This, however, is contrary to the observation of a smaller reflected pulse in the data. One possibility may be that the reflected pulse in ideal MHD will follow the field line on which it was generated, and will not arrive back at the same location as the driver flows. Nevertheless, fast tailward flows are rare in the near-Earth, near-neutral sheet magnetotail, whereas fast Earthward flows in the same region are not uncommon (Baumjohann et al., 1990). Thus the question remains, why should any evidence of a reflected BBF pulse have so small an amplitude relative to the generating, Earthward pulse.

Another related question has to do with the damping rate of the flow. At periods of  $\sim 1$  min ionospheric dissipation rates are expected to be quite small given typical values of Pedersen and Alfven conductivities (e.g., Lysak and Song). Yet, in reality BBFs last only a few Alfven bounce periods, i.e.,  $\sim 10$  minutes relative to an Alfven bounce period of 1-2 minutes (depending on latitude). If the individual flow bursts are considered (Angelopoulos et al., 1992), then those last as little as 1 minute, i.e., barely enough for the Alfvenic pulse to bounce off-of the ionosphere once.

This suggests that an energy dissipation mechanism that does not involve the ionosphere must be present, such that most of the incoming BBF-generated Alfvenic pulse dissipates its energy even before it reaches the auroral ionosphere. In this paper we present further evidence that indeed this is the case, and link the BBF observations with the aforementioned substorm-time observations of Wygant et al. (2000). In Section 2 we present a case study of a fortuitous magnetic conjunction between the POLAR and Geotail spacecraft during the course of a substorm. In Section 3 we evaluate the electromagnetic energy flux propagating along the field lines at the two spacecraft. We show that in all frequency ranges there is far more power per unit flux tube radiated towards the ionosphere at the location of Geotail at  $18 R_E$ , than is radiated towards the ionosphere at the location of POLAR at  $6 R_E$ . We also compare the electromagnetic energy flux in the tail (at Geotail) with the Earthward particle energy flux at the same place and find that the latter exceeds the former by a factor of 10. This fact, as well as careful consideration of the components of the electric and flow fields suggest that the source of the Poynting flux is the East-West motion of the equatorial plasma possibly driven by the interaction of Earthward flow bursts with the ambient plasma sheet plasma. Section 4 deals with the E-to-B ratios of the perturbations associated with the large Poynting fluxes. In Section 5 we use particle observations to infer that the regions of peak Poynting flux map in the ionosphere to the region between the polar cap boundary and the active aurorae. In Section 6 we summarize our findings and in Section 7 we argue that the dissipation mechanism is probably kinetic Alfven waves launched from the plasma sheet and dissipating much of their energy at or above the altitude of POLAR.

## 2. THE EVENT

We searched for POLAR-Geotail meridional conjunctions (footpoints within 1.5 MLT hours) in the period from 1996/03/01 to 1997/05/31, at the nightside (MLT between 2100 and 0300) and found 46 conjunction events. Only during one of those conjunctions did a substorm occur close

enough in space (i.e., in local time) and in time that both spacecraft experienced the anticipated magnetic and electric field variability associated with substorms (e.g., Keiling et al., 2000, Nagai et al., 1998). This event occurred in 1996/11/13 between 0900 and 1200 UT. Figure 1 presents the equatorial (IGRF mapping to magnetic equator) and meridional (GSM) projections of the spacecraft. POLAR was in an outbound leg of its orbit moving from below to above the magnetic equator, essentially along the 22.3 MLT meridian, while increasing in radial distance from 3.9 to 6.4  $R_E$ . Geotail was in the tail; its equatorial projection was moving more slowly than POLAR's in the Eastward and tailward direction. The equatorial footprints of the two spacecraft were along the Sun-Earth line at ~1020 UT.

Figure 2 presents the ionospheric footprints of the spacecraft using the Tsyanenko (1989) model (herein called T89 model), along with the anticipated oval location for the measured AL (Feldstein and Starkov, 1967; Starkov, 1994). The snapshot of the Earth and a superimposed corrected geomagnetic coordinate grid are shown for 1030 UT. Tick marks along the satellite footprints are every hour (same as in Figure 1); the arrow shows the direction of motion in geographic coordinates. The MLT separation of the ionospheric footprints varies from ~0.5 hours at 0900 UT to ~1.5 hours at 1200 UT.

While no space imager data was available at the time, the ground based meridional scanning photometer from Poker Flat was operating (Poker Flat was located between the Geotail and POLAR footprints at 1020 UT, though much closer to Geotail). The photometer data from Poker Flat are shown in Plate 1. The 5577A data show the discrete auroral emissions, and show evidence for a substorm precursor at 0932 UT (no significant poleward development), at 1018 UT (onset) and 1038 UT (major intensification).

The northward component (X) data from auroral-latitude ground magnetometer stations (whose positions were indicated in Figure 2) are shown in Figure 3. Based on the magnitude of the perturbations it is evident that the main substorm activity was seen near the Alaskan sector. A second substorm took place at 1310 UT, over the Russian sector, but that unrelated to our study.

The northward (X) and Eastward (Y) component data from mid latitude ground stations are shown in Figure 4. Note that EWA (Ewa Beach) was at an MLT of 23.9, while GAM (Guam) was at an MLT of 20.3 at 1030 UT. The positive excursion seen in the X-components at ~1038 UT confirms the global nature of the main substorm intensification. The opposite sign excursion in the Y component data shows that the substorm meridian was between the two stations at 1038 UT.

POLAR observations are summarized in Figure 5 for the period 1000-1200 UT. The top panel shows SCPOT, the reverse of the spacecraft potential which corresponds (in a non-linear fashion) to the ambient plasma density, measured by the EFI instrument (Harvey et al., 1995). At 1000 UT the spacecraft was in the plasmasphere, as evidenced by the large value of SCPOT. Exit from the plasmasphere occurred at ~1020 UT, possibly in response to the substorm onset. Plasma sheet/lobe densities ( $0.01-1 \text{ cm}^{-3}$ ) are consistent with the SCPOT values thereafter.

The magnetic and electric field data from the MFE (Russell et al., 1995) and EFI instruments on POLAR are shown in the XY, Z, 56 coordinate system at spin-period (6s) resolution. The unit vectors XY and Z are on the satellite spin plane, with XY opposite to the projection of the satel-

lite-sun vector on the spin plane, and with Z normal to the XY axis, positive closest to the north. The unit vector 56 is along the spin axis, in the direction such that XY, Z and 56 form an orthogonal basis. The directions of XY and 56 depend on the time of the year but are independent of the satellite spin flips which occur twice a year. For the event under study XY points roughly opposite to  $X_{GSE}$ , while 56 points roughly duskward. The large variability in the electric field data is an indication of traversal of the (high beta) plasma sheet; exit from the plasma sheet is demarcated by the reduction in such low frequency fluctuations at  $\sim 1135$ UT.

Geotail observations for the same period (1000-1200 UT) are summarized in Figure 6. Magnetic field and plasma data are plotted at 12s resolution in GSM coordinates. The electric field can be computed at the same (12s) resolution from the plasma approximation,  $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ ; its components are plotted as solid lines in GSE coordinates at the bottom three panels. Electric field data obtained from the EFD instrument are plotted on the same panels as dots at spin-period (3s) resolution. The EFD instrument measures the electric field between the tips of a spinning antenna and spin-fits of that (one dimensional) measurement are used to obtain the X and Y spin plane (near-GSE) components. The third component ( $E_z$ ) can be computed only when the magnetic field is sufficiently away (by more than  $\sim 10^\circ$ ) from the spin plane. At the times that this condition is met this computation was performed; the points are presented also as dots at the bottom panel. Typically the electric field measured by the EFD instrument agrees quite well with the electric field inferred from the plasma data, except at low flow velocities where the diamagnetic drifts ( $\sim 10$ km/s) start becoming important. At times of fast flows the electric field data at 3s resolution measured by the EFD instrument are much more variable than the 12s averages computed from the plasma data, indicating increased level of wave power that is not fully resolved at 12s resolution.

Prior to 1000 UT Geotail showed multiple traversals of the magnetic equator without significant flows or magnetic noise. At 1018 UT the magnetic field at Geotail started to show increased flaring (southward  $B_z$ , total field increase) expected during substorms tailward of the reconnection region. Geotail exited to the lobe, as evidenced by the decrease in density and temperature at 1020-1024 UT, and re-entered in an “active” plasma sheet, i.e., a plasma sheet accompanied by fast Earthward boundary layer and neutral sheet flows. The boundary layer flows at 1022-1026 UT are typical of this situation which has been termed “plasma sheet recovery”. The ensuing neutral sheet flows are typical of the bursty bulk flows studied previously (e.g., Angelopoulos et al., 1996a). The plasma sheet dipolarized at 1120 UT. Some bursty bulk flows are seen also during that dipolarization, which is expected to map at high latitudes in the auroral oval. Fast flow activity ceased at 1130 UT at Geotail, and the plasma sheet thinned at 1140 UT (evidenced by the reduction of  $B_z$  to the value it had prior to substorm onset, or a few nT). Cessation of activity at Geotail corresponds to completion of substorm recovery as evidenced by auroral zone magnetograms. The entire interval of fast flow activity at Geotail is accompanied by large amplitude fluctuations in the electric and magnetic fields.

The entry of POLAR in the plasma sheet at 1018 UT and the exit of Geotail from the plasma sheet at around the same time are most likely related to the onset of the substorm. The working phenomenological hypothesis is that the plasma sheet reconnects underneath or slightly Earthward of Geotail and the inner edge of the plasma sheet moves Earthward as a result of the associated reconnection flows. The exit of POLAR from the plasma sheet at  $\sim 1135$  UT and the plasma sheet thinning at Geotail at 1140 UT are most likely related to the completion of the substorm recovery.

The plasma sheet thinned again as part of a growth phase of the subsequent substorm which occurred at 1310 UT.

Evidently POLAR's and Geotail's large scale motions relative to distinct magnetotail regions are consistent with the substorm which occurred and consistent with each other, in accordance with their approximate alignment along the Sun-Earth direction. The large amplitude and variability of electric fields observed simultaneously at the two spacecraft are also consistent with each other. These facts suggest that the two spacecraft not only have nearby model ionospheric projections but that they were traversing flux tubes undergoing similar processes. This is ultimately why this event was chosen as a good candidate to check mapping of electromagnetic energy from high to low altitudes.

### 3. ENERGY FLUX

In this section we compare the energy flux density measured on Geotail and POLAR. Figure 7 shows the most variable of the three components of the electric field on POLAR (dEZ) and the associated magnetic field component (dB56), after high-pass filtering components EZ and B56 of Figure 5 through subtraction of a running average with a 10 minute window. After forming the Poynting flux in the XY, Z, 56 system, we obtain its field aligned component by dotting it with the unit magnetic field vector obtained after averaging the magnetic field data with a 10 minute-window running average. The resultant parallel Poynting flux in units of  $\text{ergs/cm}^2\text{s}$  is plotted on the top panel of Figure 7 (SPAR).

One caveat here is that the E56 component, used in the computation of SPAR requires offset corrections which are non-trivial. The offsets depend on the ambient density (and less so on the electron temperature), as evidenced by the anti-correlation between the low frequency component of E56 and the low frequency component of SCPOT (proxy for plasma density) in Figure 5. However, we are concerned only with the high frequency part of the fluctuations in the computation of SPAR, which is least affected by such offset uncertainties. To verify the behavior of SPAR we also computed the E56 component under the assumption that  $E \cdot B = 0$  and use it to recompute the parallel Poynting flux. This is denoted SPAR0 and is also plotted in Figure 7. The computation of E56 can be done safely when the magnetic field is sufficiently away from the spin plane, or when B56 is no less than 15% of the total field value. The SPAR0 component in Figure 7 compares quite favorably with the SPAR component, which gives credence to our assumption that offset corrections for the high pass filtered E56 are negligible.

It is evident that the Poynting flux is directed along the field line (towards Earth) and that although a low frequency oscillation dominates the magnetic field fluctuations the Poynting flux is composed of pulses no longer than a couple of minutes in duration. These are very similar attributes of the computed Poynting flux at that altitude as described by Wygant et al. (2000). What is different from the events described by Wygant et al. is the amplitude of the electric, magnetic and Poynting flux pulses, which are a factor of 5 smaller here than in the substorm events selected by Wygant et al. (2000). This is not due to the activity (AL was  $\sim -100$  nT for one and  $-1500$  nT for the other of the two Wygant et al. events, while our event occurred during intermediate negative bay magnitudes of  $\sim 400$  nT). Rather, it is most likely due to the selection by Wygant et al. of the largest electric field events in the course of a year (1997). The large magnitude of the Wygant et al. events

may have to do with the fact that their crossings are both inbound. Typically an active time plasma sheet boundary is crossed when the boundary moves past the spacecraft. Near substorm onset the inner magnetosphere is compressed, which typically brings the plasma sheet boundary inward. An inbound orbit remains longer at the plasma sheet boundary, and can resolve spatial structures at the 6 s spin-period resolution better than an outbound orbit.

Testimony to that interpretation is the fact that when high time resolution (40 points/second) data are used then the peak absolute amplitude of the oscillations for our event is comparable to the peak absolute amplitude of the events of Wygant et al. (i.e.,  $\sim 200$  mV/m). This is shown in Figure 8 for a subset of the data near the plasma sheet boundary layer. In that figure the three components (XY, Z, and 56) of both the electric and magnetic fields are plotted in dotted lines. The solid lines represent the data rotated in the coordinate system “ijk” determined from the principal axes of the electric field variance matrix. The maximum variance axis, “i”, is closest to the Z direction, the minimum variance axis, “k” is nearly aligned with the XY direction (as expected since  $E \cdot B = 0$  to within experimental uncertainties and BXY is the dominant magnetic field component) and the intermediate variance axis “j” is closest to the 56 direction (duskward). An angle of  $30^\circ$  exists between the “i” and the Z directions. Assuming that the magnetic fluctuations are due to crossings of field aligned currents sheets aligned with the plasma sheet boundary surface, this angle denotes the angle between the plasma sheet boundary normal and the  $Z_{GSE}$  axis. The value of  $30^\circ$  is quite reasonable given the large undulations of the plasma sheet boundary surface that have been reported during substorms using other techniques (Kettmann and Daly, 1988). Note that the coordinate system chosen is near identical to the coordinate system which can be obtained from the principal axes of the magnetic variance matrix. It is also noteworthy that in both systems the parallel component of the electric field is consistent with zero.

The low frequency (spin-resolution) peak Poynting flux (from Fig. 7) is  $0.25 \text{ ergs/cm}^2\text{s}$  which, when mapped to the auroral ionosphere with a mapping factor of 125 (ratio of ionospheric and local values of magnetic field is  $\sim 50,000 \text{ nT}/400 \text{ nT} = 125$ ) gives  $31 \text{ ergs/cm}^2\text{s}$ . The full resolution (40 points/s) data peak Poynting flux (from Fig. 8) is  $1.25 \text{ ergs/cm}^2\text{s}$  and occurred in an ambient field of 280 nT. When the appropriate mapping factor ( $50,000 \text{ nT}/280 \text{ nT} = 178$ ) is used the ionospheric equivalent is  $\sim 220 \text{ ergs/cm}^2\text{s}$ , i.e., comparable to the largest events selected by Wygant et al., 2000. This energy flux is  $\sim 2$  orders of magnitude larger than the typical fluxes seen below the auroral acceleration region (Kelley et al., 1991).

Mapped to an 800 km altitude the low and high frequency peak Poynting fluxes are  $19 \text{ ergs/cm}^2\text{s}$  and  $138 \text{ ergs/cm}^2\text{s}$  respectively (mapping factors of 75 and 110 respectively). The largest fluxes of downgoing electrons seen at DMSP altitudes have energy flux density of  $100 \text{ ergs/cm}^2\text{s}$  (e.g., Newell et al., 2000). Thus the high resolution Poynting flux measured at POLAR can account for the energy of accelerated electrons measured below some of the largest arcs seen on DMSP. As argued by Wygant et al., (2000) the upward secondary electrons do not exceed  $25 \text{ ergs/cm}^2\text{s}$  within arcs (Stenbaek-Nielsen et al., 1998), while upflowing ion energy flux mapped to 100 km altitude is only a fraction (a few percent) of the energy of the downgoing electrons within arcs (Ghielmetti et al., 1979). Even at the poleward boundary, where such ion outflow fluxes maximize

(Carlson et al., 2000), and even at storm times the largest energy fluxes are on the order of 10 ergs/cm<sup>2</sup>s, when mapped to 100km altitude (McFadden et al., 2001). Therefore the Poynting flux observed during our event can account for the energy deposited in the particles in the auroral acceleration region. This conclusion is in agreement with the findings of Wygant et al., (2000).

The presence of Geotail on the same meridian as POLAR provides readily a measure of the energy flux available at that distance. Figure 9 shows computations of the Poynting and the particle energy flux at Geotail. The Poynting flux is computed two ways: Using the electric field measured by EFD (3s resolution) and using the electric field computed from the plasma approximation (12s resolution).  $E_z$  is the largest of the three components of the computed electric field as evidenced in Figure 6. Since  $E_z$  is not measured by EFD but is a quantity derivable only when the magnetic field is favorably oriented (away from the spin plane)  $E_z$  is not available at 3s resolution all the time. Instead of using incomplete data we obtained the three components of the perpendicular electric field assuming the electric field was all in the XY plane. This is an underestimate of the full electric field. The perpendicular component of the EFD-measured electric field in the Z direction is non-zero but small (i.e., mostly immeasurable), and is shown as dots in the bottom panel of Figure 9, along with  $E_z$  computed from the plasma data at 12s resolution (solid line). We subtracted a 10 minute-window running average from both the magnetic field and plasma data (two bottom panels) before computing the Poynting flux.

As mentioned earlier,  $dE_z \cdot dB_y$  is the largest contributor to the parallel Poynting flux at Geotail. As evidenced by looking at Figure 6,  $E_y$  is the largest contributor to the cumulative (Earthward) magnetic flux transport due to its non-zero average value over the event, yet the fluctuation amplitude in  $E_z$  is larger than that of  $E_y$  (and far greater than that of  $E_x$ ) at Geotail. The similarity of the trace of  $E_z$  to  $V_y$  shows that the term  $-V_y \cdot B_x$  is the most important contributor to the  $E_z$  fluctuations and consequently to the Poynting flux. These dawn-dusk flows have been noted before (e.g., Angelopoulos et al., 1994) but they do not contribute significantly to a net transport. Their average over many bursty flow events is a small duskward component consistent with diamagnetic drifts of particles. According to our observations, these  $V_y$  flows are the origin of the field-aligned Poynting flux measured at Geotail.

The Poynting flux component parallel to the magnetic field, SPAR, points predominantly opposite to the field direction; since Geotail was below the neutral sheet this means the flux was directed away from the neutral sheet and into the ionosphere. The peak Poynting flux is on the order of 0.1 ergs/cm<sup>2</sup>s at a resolution 3s-12s. When mapped to the ionosphere (mapping factor of  $\sim 50,000/20=2,500$ ) it corresponds to 250 ergs/cm<sup>2</sup>s, i.e., approximately an order of magnitude larger than the value computed earlier from POLAR at a similar time resolution (31 ergs/cm<sup>2</sup> s at 6s resolution). Despite the fact that the SPAR computed at 3s resolution from the perpendicular component of the 2-dimensional electric field data is an underestimate of the true value of SPAR, its peak value is larger than the peak value of SPAR computed from the plasma data at 12s resolution. This means that (much like in the case of POLAR) higher frequency data could result in even higher Poynting flux peak values.

Since the EFD instrument is a single axis measurement of the electric field it is not possible to obtain routinely the three components of the electric field. However, the projection of the instantan-



neously measured electric field along the X and Y axes, and the approximation that  $E_z=0$  can result in a proxy of the real electric field. When the perpendicular component of that is considered (i.e., E-parallel is ignored) the resultant parallel Poynting flux measurement is a lower limit of the actual parallel Poynting flux. The problem with this method is that it ignores the  $E_z$  variation, which, according to the electric field values as computed from the plasma data may be the dominant one (see Figure 6). To amend this deficiency completely is impossible with a 1D measurement which is always obtained normal to the direction of interest (Z). A way to occasionally infer some information about the value of  $E_z$  is to look for times when the Z-component of the magnetic field is a large fraction of the total field (the larger the fraction the higher the confidence). At such times we can obtain a better estimate of the  $E_z$  component by using the projections of the antenna measurement on the X and Y axes and the  $E \cdot B=0$  approximation.

Such was that case (only for a short period during the event considered) at  $\sim 10:41:24$  UT. The interval is shown in Figure 10. The electric and magnetic field data have been detrended (high-pass filtered) by subtracting a 20sec-window running-average and then they were running-averaged at 0.1 resolution. These bandpass filtered data are shown as dE and dB quantities. Also shown in the dBx panel is the X-component of the magnetic field, Bx, for reference. The spin phase angle between the boom and the X-axis is shown also. The electric field data show spikes of the order of 50mV/m (occasionally these spikes exceed the maximum digitization level of the instrument) and those spikes correspond to peaks in the Poynting flux. But at  $\sim 10:41:24$  UT a partial entry near the plasma sheet (evidenced by a decrease in the value of Bx) permitted computation of the third component ( $E_z$ ) from the projection of the boom-aligned electric field measurement on the X and Y axes. This results in a peak in dEz and the resultant Poynting flux at a value of  $0.23 \text{ ergs/cm}^2\text{s}$  directed towards the ionosphere. When mapped to an altitude of 100 km (mapping factor of  $50,000\text{nT}/18\text{nT}=2780$ ) we obtain a value of  $640 \text{ ergs/cm}^2\text{s}$ , which exceeds the values obtained from mapping POLAR Poynting fluxes by a factor of 3. Since the Geotail measurements are a lower limit of the true Poynting flux values, our conclusion is that the high frequency spectrum (up to 0.1s resolution) of the Poynting flux at Geotail also shows the same trend as the lower frequency spectrum, i.e., that its ionospheric projection is several times larger than values obtained near-simultaneously on POLAR.

We now turn to the particle energy flux measured at Geotail. This is the energy flux, Q, and includes the kinetic energy flux, thermal energy flux and magnetic energy flux. The dominant term is the thermal energy flux, since in a high-beta plasma both the flow speed and the Alfvén speed are smaller than the thermal speed. Since in bursty bulk flows the preferential direction of motion is the X-direction,  $Q_x$  will dominate over the other components. We present in Figure 9 (top panel)  $Q_x$  in  $\text{ergs/cm}^2\text{s}$ . This ought to be compared with the local measurements of the Poynting flux at the same time resolution (12 s) as obtained from the plasma instrument; it is evident that the peaks in the particle energy flux are one order of magnitude larger than the peaks in the Poynting flux. This suggests that if only a small fraction of the equatorial particle energy flux is converted to electromagnetic energy in the form of propagating Alfvén waves along the boundary, then it is sufficient to account for the locally measured Poynting flux. In fact, it is reasonable to expect that a significant fraction of the BBF energy will indeed couple to adjacent plasma sheet regions and will radiate Alfvén waves along the plasma sheet boundary.

The above relationship of energy budgets along the auroral flux tubes during substorms is not confined to the short-lived peaks in the Poynting flux, but rather persists in all frequency ranges, as evidenced in Figure 11. Shown in the bottom panel of that figure is the spectrum of the energy flux (the square-root of the power spectral density) in units of energy flux per root Hz. When mapped to a common altitude (100 km) at the ionosphere the energy flux spectra from the different satellites can be readily compared. This is done in the top panel of Figure 11. It is evident there that in all frequencies the Poynting flux measured at POLAR is an order of magnitude smaller than the Poynting flux measured at Geotail. It is also evident that in all frequency ranges the particle energy flux measured locally at Geotail is one order of magnitude larger than the Poynting flux measured on the same satellite. These results are only weakly dependent on the interval selected within this active period. In fact, the fluctuation amplitudes of plasma and field data measured at Geotail are typical of BBFs and the peak energy flux values (for both SPAR, Qx) are expected during most BBF intervals. Moreover, the results obtained from spectral comparisons the energy flux hold when the most active 20 min interval at Geotail is compared with the most active (though different) 20 min interval at POLAR during the same substorm event.

#### 4. E-TO-B RATIOS

In an effort to understand whether the waves are propagating Alfvénic waves or spatial structures closing through the ionosphere we plot in Figure 12 the ratio of E over B versus frequency for both spacecraft. The plots are normalized to the local Alfvén speed. In the case of Geotail we used the  $E_z$  component inferred from the plasma flow at frequencies below 1/24 Hz, and the  $B_y$  component at the same (12s) resolution. The  $E_y$  and  $B_z$  components were used between 1/24 Hz and 1/6 Hz (at 3 sec resolution) after checking that at lower frequencies the  $E_y/B_z$  ratio was equal to or somewhat larger than the  $E_z/B_y$  ratio. The  $Y_{GSM}$  projection of the electric field measured along the double-probe axis and the measured  $B_z$  were used for frequencies higher than 1/6 Hz, but only up to 10 Hz since the sensitivity of fluxgate magnetometers starts decreasing at around 10Hz. In the case of POLAR, the ratio of power in the  $EZ$  and  $B56$  components were used at all frequencies.

Also plotted for each frequency regime in Figure 12 is the inverse of the nominal, height integrated Pedersen conductivity,  $\Sigma_p = 10$  mhos, anticipated at the auroral ionosphere. Spatial structures closing through the ionosphere are expected to have  $\delta E/\delta B$  ratios that are equal to  $1/\mu_0 \Sigma_p$ .

On Geotail, it is evident both in the frequency dependent E-to-B ratios of Figure 12 and also by simply taking the ratio of the perturbation amplitudes of  $\delta E_z$  ( $\sim 30$  mV/m) and  $\delta B_y$  ( $\sim 10$  nT) during the 10:41:24.5 UT Poynting flux spike in Figure 10, that the E-to-B ratio is  $\sim 3000$  km/s, which is twice the local Alfvén velocity ( $\sim 1400$  km/s). Thus, if the structures which are responsible for the peak Poynting flux at Geotail are indeed Alfvén waves then they are likely in the kinetic regime.

On POLAR, structures below 0.05 Hz are consistent with spatial structures, especially if lower values of Pedersen conductivity are used ( $\sim 1$ -5 mhos). Fluctuations at frequencies between 0.05 and 1 Hz are consistent with Alfvénic structures, whereas higher frequency fluctuations may be, at least partly, electrostatic waves. Some of those waves are evident in the  $\delta E_z$  component in Figure

8 as  $\sim 1$  sec period, and  $\sim 0.15$  s period waves, modulating the large amplitude electric field structure. However, the rise-and-fall time of the large electric field structure associated with the Poynting flux peak is  $\sim 5$  seconds and the E-to-B ratio in the associated frequency range (0.2 Hz) is near the Alfvén velocity. As evidenced by taking the ratio of the electric to magnetic perturbations near the Poynting flux of Figure 8,  $\delta E/\delta B \sim (150 \text{ mV/m})/10 \text{ nT} \sim 15,000 \text{ km/s}$  which is about 2.5 times the local Alfvén speed ( $\sim 6,150 \text{ km/s}$ ). Thus, if the above structure, which is associated with the peak value in Poynting flux, is Alfvénic, it is also, quite likely, kinetic.

## 5. IONOSPHERIC PROJECTION

Plate 2 shows the ion and electron differential energy flux spectra during the last part of the POLAR plasma sheet crossing, encompassing the interval plotted in Figure 8. It is evident that during the crossing of the outermost Lshells of the plasma sheet, upflowing ion bursts of energies 0.5 - 10 keV were seen at POLAR. In the same period, field aligned electrons (into or out of the ionosphere) at energies 0.05 - 2 keV are evident. At the time of the large Poynting flux spike plotted in Figure 8 one of the largest energy and intensity upflowing ion beams was seen (marked by the vertical arrow above the upper panel and below the bottom panel). The ratio of differential energy fluxes between downgoing and upgoing electrons is shown in Figure 14. The downgoing electrons of energy  $\sim 0.05$ -2 keV dominate over the upgoing electrons of the same energy. The opposite scenario occurs at other instances. The observation of upflowing ions and counter streaming electron beams at the times of the peak Poynting flux at POLAR identifies the region in the ionosphere where POLAR maps. According to FAST observations (Carlson et al., 2000), these are features characteristic of particle populations poleward of the inverted V region. This region (nightside oval poleward of the aurora) is responsible for some of the largest ion outflows seen around the oval. The electron acceleration there can occur as a result of the acceleration of plasma sheet electrons by Alfvén waves (Chaston et al. 2000) which are in the inertial regime (Lysak and Lotko, 1996).

Plate 3 shows the Geotail electron distribution on the XY plane (in spacecraft coordinates, which are close to GSE) at two times prior to (but near) the observation of the large Poynting flux spike of Figure 10. The line-plots to the right of the polar plot are the distribution function velocity spectra, with the red line representing the spectrum along the red mark on the polar plot (sector 13, near-antisunward direction, i.e., parallel to the field) and the green line representing the spectrum in the opposite direction (near-sunward direction, parallel to the field). One full Geotail distribution is measured once per spin (3 seconds); distributions are averaged on-board for 4 spins. The distribution during the 12 seconds encompassing the time of the spike is not available but the distribution prior to it is the one presented at the bottom of Plate 3. It is evident that the electron distribution is anisotropic. Similar anisotropic electron distributions are observed throughout this active period, and in other Geotail observations of fast flows. The details of the distribution shown at the bottom of Plate 3, i.e., low energy electrons (below 1 keV) being mostly towards the Earth and high energy electrons (above 1 keV) being mostly towards the tail are not to be trusted because of temporal aliasing. But the low-energy bi-directional anisotropy is present, on-and-off, throughout the event with either the field aligned or the field opposed direction having larger fluxes. For example, the distribution shown on the top of Plate 3 was taken about 1 minute earlier than that at the bottom of the Plate, with one (less anisotropic) distribution available in between. The spacecraft potential, as measured by Geotail/EFD was on the order of 40 eV or less at that time, and

energies affected by photoelectron contamination have been removed from the plot presented. The important thing here is that low energy electrons ( $\sim 100$  eV) show a field aligned anisotropy in the Earthward direction in the top distribution while the same energy electrons have a tailward anisotropy in the bottom distribution.

The transient, anisotropic nature of the low energy electron distributions suggests that bidirectional electron beams may be present at time scales which are not resolved by the accumulation rate of the Geotail plasma instrument (shorter than 12 seconds). The parallel flux of the 100 eV electrons at Geotail is  $\sim 10^{-17} \text{ s}^3 \text{ m}^{-6}$ , which is similar to the one observed at POLAR in the same energy range (Figure 14). This further reinforces our earlier conjecture that POLAR and Geotail were along flux tubes which undergo similar processes, i.e., on flux tubes that connect to the region poleward of the auroral arcs.

The presence of copious amounts of electromagnetic energy radiated from the altitude of Geotail towards the ionosphere suggest that the ultimate source of the energy that accelerates the electrons and ions is most likely the bursty bulk flows, and that the energy propagates towards Earth in the form of Alfvén waves.

## 6. CONCLUSIONS

Comparisons of the field-aligned Poynting flux at POLAR and at Geotail, after accounting for mapping along flux tubes to the same reference altitude of 100km, show that in all frequency ranges between 1mHz and 0.1Hz the electromagnetic energy generated at Geotail exceeds the one measured at POLAR by a factor of 10. This situation continues in the range 0.1Hz to 10 Hz, where peak Poynting fluxes measured at Geotail exceed those measured at POLAR by at least a factor of 3. This suggests that energy dissipation takes place along auroral field lines and before it reaches POLAR.

Our comparisons of the peak Poynting flux measured at POLAR during this substorm event with the anticipated Poynting flux measured below auroral field lines suggests that the peak Poynting flux at high time (1/40s) resolution exceeds that anticipated by in situ ionospheric measurements by a factor of 100. The amount of energy flux measured at POLAR is comparable to the largest energy fluxes observed in the precipitating electrons (plus upflowing ions and secondary electrons) during substorm times.

At frequencies below 0.05Hz E-to-B ratios on Geotail are consistent with Alfvénic oscillations whereas on POLAR they are below the Alfvén speed. For low values of the ionospheric conductivity low frequency waves on POLAR are consistent with current filaments closing through the ionosphere. At frequencies of around 0.05-1 Hz, where the largest Poynting flux peaks are observed at both spacecraft, the E-to-B ratios at Geotail are many times larger than the local Alfvén speed and consistent with kinetic Alfvén waves, whereas at POLAR they are in the Alfvénic regime. The parallel electric field associated with the POLAR peak Poynting fluxes is below the uncertainty arising from spin vector knowledge inaccuracies ( $\sim 1 \text{ mV/m}$ ).

The presence of anisotropic electrons observed at or near the times of peak Poynting flux on both spacecraft reinforces our conjecture that the two spacecraft map along field lines that undergo

similar processes. The observation of peak-flux and peak-energy upflowing ions on POLAR simultaneous with the anisotropic electrons and the peak Poynting fluxes suggests that the region where both spacecraft map is just poleward of the parallel potential associated with the auroral structures.

## 7. DISCUSSION

### 7.1 On the generation of $V_y$ flows.

It is remarkable that despite the dominance of the  $V_x$  flows (and the secondary nature of the  $V_y$  flows) in terms of energy transport, the  $V_y$  flows measured at Geotail appear to dominate in terms of their contribution to the Poynting flux out of the plasma sheet and into the auroral ionosphere. This situation may be even more pronounced at higher frequencies, where peak Poynting fluxes due to  $E_z$  fluctuations are inferred at Geotail. In retrospect this should have been anticipated since the  $V_x$  fluctuations ( $E_y$  fluctuation electric fields) are heavily damped due to the coupling between the Alfvén and the slow mode, arising from the field line curvature (Southwood and Saunders, 1985).

The generation of  $V_y$  fluctuations in connection with bursty flows is difficult to ascertain without multiple satellites. However, it is reasonable to expect that the interaction of localized Earthward jets of plasma with the pre-existing (relatively slow or stationary) plasma sheet plasma would drive significant East-West plasma motion. Such is the case in observations by Sergeev et al., (1996) of localized bursty flow structures, therein termed “bubbles” in reference with the theoretical model of Chen and Wolf (1993). These authors used two satellites to study the properties of the incoming flow when the magnetic field had a sharp boundary that permitted usage of the minimum variance technique to determine the satellite location relative to the East-West center of the structure. It was found that not only the flow deflected downward when the satellite was located duskward of the flow center (and vice-versa on the other side) but also that the magnetic field was deflected consistently, i.e.,  $B_y$  had the correct sign expected if the field lines were swept sideways along with the flow. Multiple localized flow bursts, which are common within BBFs, thus will naturally cause considerable  $V_y$  fluctuations and a resultant large, fluctuating  $E_z$  field.

An alternative (and most likely co-manifest) process that ought to result in large Poynting fluxes is the process of magnetotail reconnection. Since the reconnection process in the tail is transient and localized (e.g., Angelopoulos et al., 1996b), we expect that the ionospheric area mapping directly to the reconnection site(s) is limited relative to the area affected by the resultant flows and their shear.

### 7.2 On mapping

An exact mapping along field lines is rather difficult to obtain over large distances. In this paper we resorted at comparing Poynting flux increases observed at different times but during the same phase of the substorm (recovery phase). In fact, the event chosen represents the most viable candidate for comparison because of the similarity of the features on the two spacecraft (large variability in fields, encounters of similar plasma regions) and the substorm which was taking place simultaneously. The times of observation are probably related to spatial motions of the active

region past the satellites, rather than temporal intensifications. The peak Poynting fluxes at the two satellites are then the most relevant quantities to compare. Supporting evidence of our mapping along flux tubes undergoing similar processes is the observation of bi-directional electron streaming on both spacecraft at, or near the time of observation of peak Poynting flux.

One might still argue that since the POLAR and the Geotail Poynting flux “spikes” occur at different times, they may represent different magnitude intensifications and therefore they cannot be readily compared. However, the properties of the electric field and Poynting flux on POLAR are typical of most active time crossings of the plasma sheet boundary by POLAR (Wygant et al., 2000) while the properties of the plasma, electric field and Poynting flux at Geotail are typical of BBFs (Angelopoulos et al., 1994). Thus, although the peak Poynting fluxes compared may not be along the same flux tubes, they are typical of the regions traversed by POLAR and Geotail at substorm recovery. The event studied, selected amongst many candidates due to the similarity of the features on both satellites during the course of a substorm, epitomizes what in retrospect seems obvious by event studies on the individual satellites: There is plenty more Poynting flux escaping from the tail than measured at 5-6  $R_E$  above auroral field lines, by a factor of about 10.

### 7.3 On energy dissipation

It is possible that energy loss is due to partial reflection along field line. To evaluate this we considered the relative change of the Alfvén conductivity per unit wave travel time in a realistic magnetic topology (T89 model). We found that this quantity differs only slightly from its value in a dipole geometry (Mallinicrodt and Carlson, 1978), and is very close to zero compared to its value at low altitudes ( $<4 R_E$ ). This suggests that waves cannot really be reflected between POLAR and Geotail. Another argument against partial reflection is that reflected waves would be broadened and would have resulted in large upward moving Poynting flux, something that is not observed here.

Alternative explanations to the energy loss is dissipation along field line or escape of wave power across field lines, both of which require the presence of dispersive Alfvén waves. Kinetic Alfvén waves were proposed initially by Hasegawa and Chen (1975) to explain heating of electrons and ions at a resonant layer on magnetospheric (and tokamak) field lines by a surface wave at the magnetopause (driver). The concept is that when the incoming compressional oscillations reach the resonant layer they become kinetic, now propagating across the magnetic field due to the finite perpendicular wavelength supported by the finite ion gyroradius and/or the finite electron inertia. In the collisionless regime the parallel electric field of the kinetic Alfvén wave interacts and heats primarily the electrons. The possibility of the existence of kinetic Alfvén waves at the plasma sheet boundary was utilized in the thermal catastrophe model of substorms (Goertz and Smith, 1989) in which the incoming waves were plasma sheet boundary layer surface waves and the kinetic Alfvén waves were excited through mode-conversion of these compressional surface waves. The presence of a magnetic field and plasma pressure gradient at the boundary layer was the reason for mode conversion of the incoming waves.

The kinetic Alfvén waves (which are operational in the regime  $m_e/m_i < \beta_e < 1$ ) and their distinction from the inertial Alfvén waves (which depend on finite electron inertia and are operational in the

regime  $\beta_e < m_e/m_i$ ) were recently discussed by Lysak and Lotko (1996). By using typical plasma sheet electron temperatures (0.5 keV) and densities ( $0.2 \text{ cm}^{-3}$ ) and a realistic magnetic field model (T89) it is possible to show that regions above  $5 R_E$  have an electron beta between  $m_e/m_i$  and 1. The electron beta exceeds 1 either near the plasma sheet boundary at distances beyond  $\sim 18 R_E$  when the Alfvén speed decreases considerably, or as soon as the field line penetrates very deeply near the neutral sheet i.e., when the ion beta  $> 7$  for a typical Ti/Te $\sim 7$  (Baumjohann et al., 1989). In our case, the entire region between Geotail and POLAR (except for the layer near the center of the plasma sheet of  $\beta > 7$ ) can support kinetic Alfvén waves of the regime discussed in Hasegawa and Chen (1974) and Lysak and Lotko (1996). Since there is ample power in the bursty bulk flows to generate the Poynting fluxes observed along auroral/plasma sheet field lines, there is no need to invoke an external global mode oscillation for generating kinetic Alfvén waves, as was done by earlier authors. Instead, the waves will be kinetic if the driver has perpendicular scale-lengths  $\lambda$  comparable to  $2\pi r_i$ . For layers adjacent to the neutral sheet ( $B \sim 10 \text{ nT}$ ,  $T \sim 4 \text{ keV}$ ) this value is  $2\pi r_i \sim 1 R_E$ . This is within the range of anticipated cross-scale size of BBFs (e.g., Angelopoulos et al., 1997).

More precisely, when the T89 mapping is used to map a BBF of an equatorial scale size of  $\sim 1 R_E$  (range  $0.2 - 2 R_E$  is used) along the field lines and compare that with the ion gyroradius, assuming a 4 keV ion temperature we obtain the results of Figure 14. For example, for a BBF equatorial scale-size of  $1.5 R_E$ , and assuming that finite wavelength effects start are important for scale-lengths equal to or greater than  $2\pi r_i$ , then the Alfvén waves will remain kinetic down to at least an altitude of  $15 R_E$ . In reality, kinetic effects will be important if the mapped scale-lengths are only a fraction of  $2\pi r_i$ , e.g.  $0.2 \cdot 2\pi r_i$ , in which case the critical distance below which such effects will be important for a  $1 R_E$  cross-scale size BBF will be obtained from the crossover of the curve labeled 0.2 with the curve labeled  $2\pi r_i$ . This distance is  $\sim 6 R_E$ , i.e., the POLAR altitude. It is thus evident that between POLAR and Geotail altitudes the scale size of the bursty flows are in the kinetic Alfvén wave regime (i.e., of the order of  $2\pi r_i$ ) simply due to the anticipated scale-size (or structuredness) of the driver. The parallel electric field associated with such structures may be very small and depends on the perpendicular wavelength of the waves, with longer wavelengths having smaller parallel fields. Thus our observation of a parallel electric field below the  $1 \text{ mV/m}$  confidence level on POLAR is not inconsistent with kinetic waves.

Next we estimate the effects of Poynting flux escape along the flux tubes connected to the bursty flows on the flow evolution. This represents a loss term to the incoming Earthward particle energy flux. We assume a box geometry in the equatorial plasma sheet. The flow is going Earthward and decelerating, while Poynting flux is escaping along field lines. No heating is assumed to occur within the box. Assuming that most of the energy is lost along the field line before it reaches the altitude of POLAR (a distance  $L \sim 10 R_E$ ) we seek the time scale within which the bursty flow will deposit all its energy via Poynting flux. Since most of the particle energy flux is in the term  $V_x \cdot P$  (Angelopoulos et al., 1994) the rate of change of the particle energy is  $\Delta V_x \cdot P_i / \Delta x$  while the rate of change of electromagnetic energy is  $\Delta S / L$ , times a factor of two for the northern and southern ionosphere. Equating the two we obtain  $\Delta x / \Delta V_x = 0.5 \cdot P_i \cdot L / \Delta S$ . This quantity has units of time and represents the time-scale for stopping of the BBF due to radiation of electromagnetic energy away

from it. Substituting the typical values of the Poynting flux measured at Geotail ( $0.01 \text{ ergs/cm}^2\text{s}$ ) and for typical ion pressures ( $P_i=0.13 \text{ nPa}$  arising from  $T_i=4\text{keV}$  and  $N_i=0.3 \text{ cm}^{-3}$ ) we obtain a time scale of  $\sim 10$  minutes. This is close to the observed median BBF duration. If we take peak values of Poynting flux at Geotail ( $0.1 \text{ ergs/cm}^2\text{s}$ ) then the stopping time is 10 times faster, i.e., 1 minute. The latter is more appropriate for individual flow bursts. In the above calculation the pressure gradient and the change in the magnetic field has been assumed small. Close to Earth these are significant. But far from Earth where the tailward gradients are weak the above calculation suggests that enough power escapes via Poynting flux along the field to account for BBF deceleration.

This can explain why bursty flows far from Earth can be seen without near-Earth flow consequences (Coroniti et al., 1979; 1980, Oieroset et al., 2000) and without any significant auroral electrojet intensifications. Much of their energy can couple through flow shear to dawn-dusk flow components which radiate electromagnetic energy along field lines. Much of that energy couples into electron heating and/or is radiated out of the flux tube. High latitude filamentary currents which are seen during mid-tail flow occurrence can be explained as due to currents carried by the the remaining portion of the Alfvén waves when they propagate to lower altitudes. Dissipation there (below an altitude of  $5 R_E$ ) is expected to take place due to the waves' parallel electric field interaction with electrons, as those waves become inertial (e.g., Chaston et al., 2000).

The above scenario can also explain why any tentative candidates for an ionospherically reflected pulse from the incoming flow burst in the data are small in amplitude relative to the incoming flow, as mentioned in the introduction. The explanation is that due to the kinetic nature of the wave (parallel electric field, finite perpendicular wavelength) most of the energy is deposited through wave-particle-interactions and/or is diffused away from the flux tube as the wave travels to the ionosphere prior to its first bounce.

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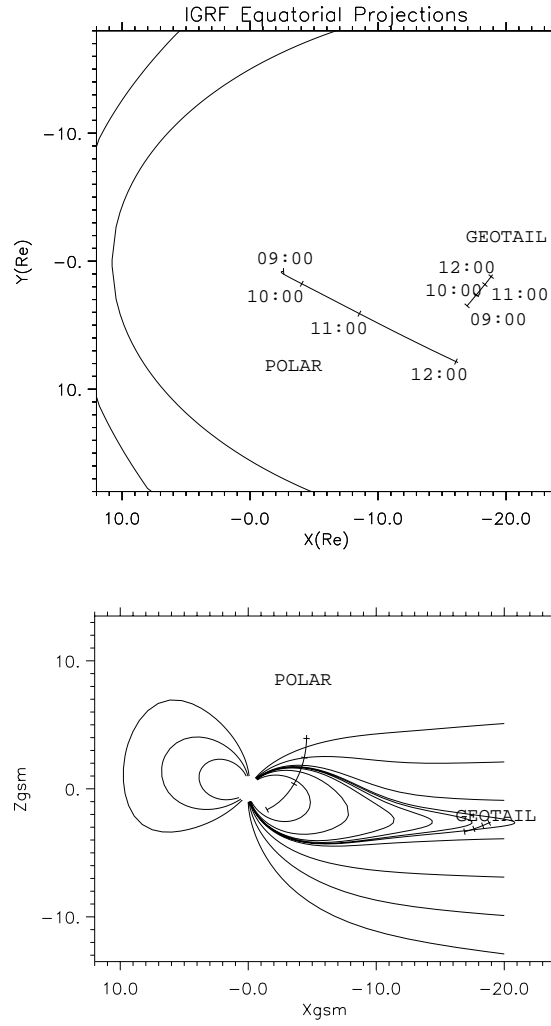
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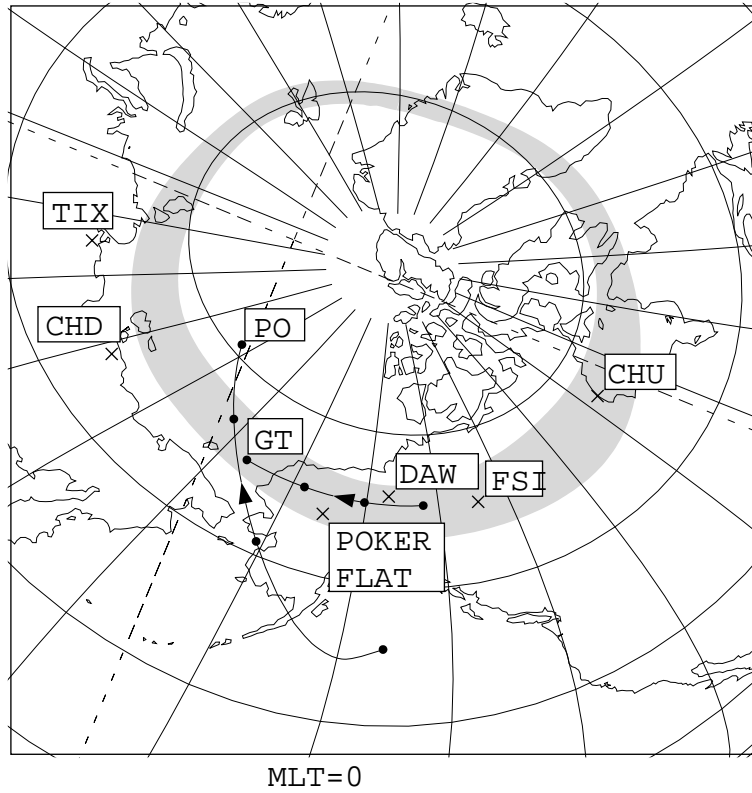
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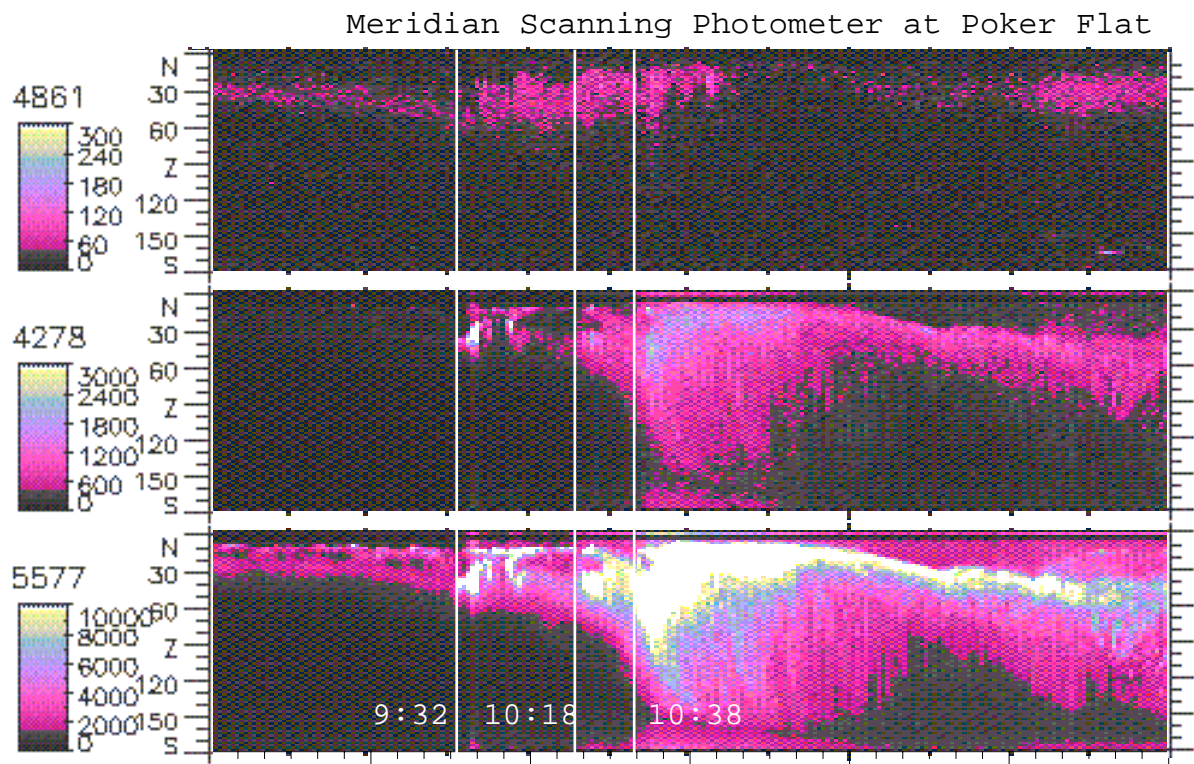
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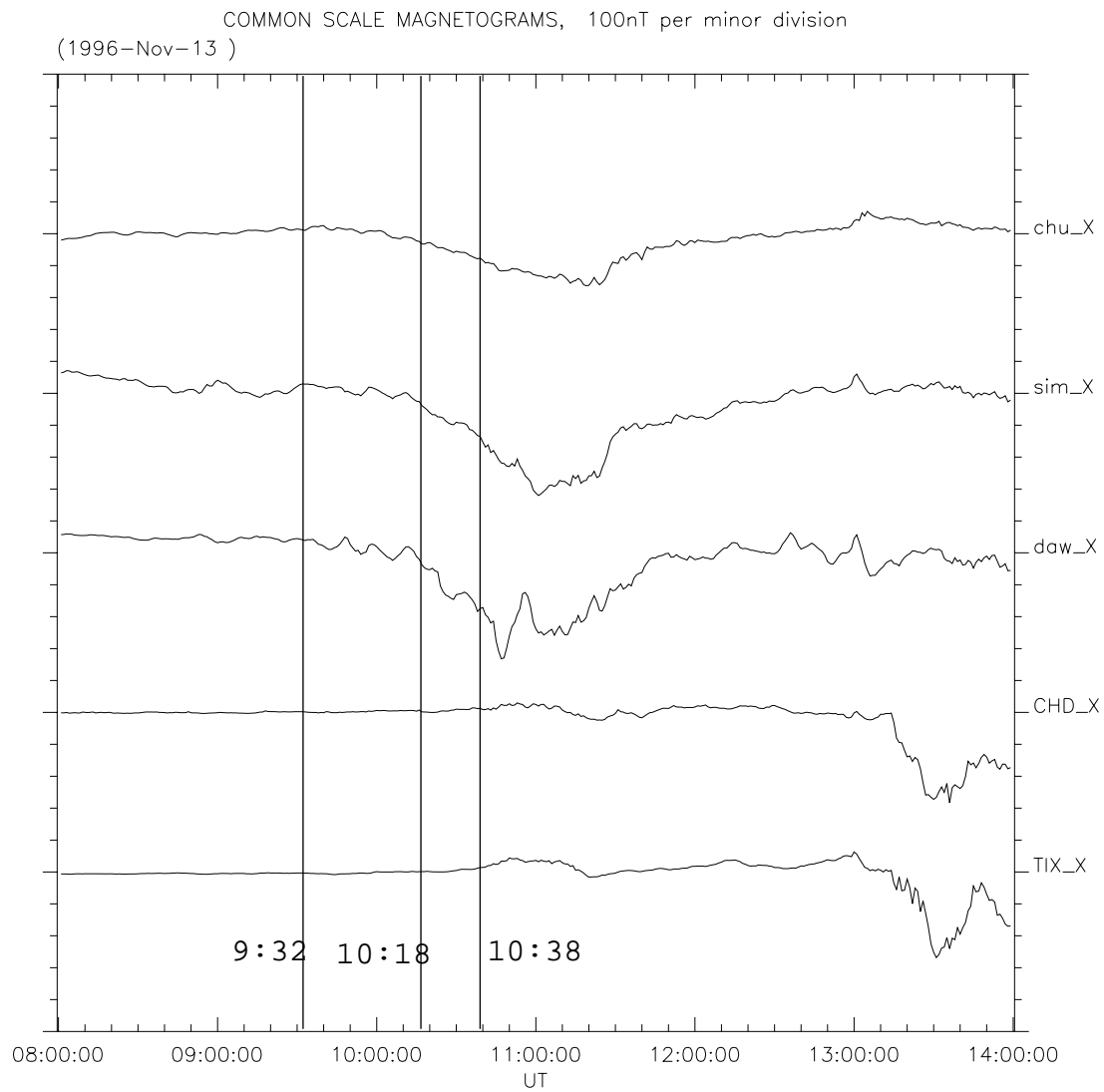
**Figure 1.** Top: Equatorial projections of POLAR and Geotail spacecraft during the interval 0900-1200 UT, on November 13, 1996, using the IGRF model. Bottom: X-Z GSM projections of the same spacecraft along with projections of magnetic field lines from the T89 (Tsyganenko, 1989) model having equatorial footpoints in the noon-midnight meridian. Tick marks are every hour.



**Figure 2.** Ionospheric magnetic footprints of POLAR and Geotail using the T89 model and shown in geographic coordinates. The snapshot of Earth is shown at 1030 UT. A corrected geo-magnetic (CGM) coordinate system is superimposed on the globe for the same time. Superimposed also is the Feldstein and Starkov (1967) auroral model for the activity level at the time (Starkov, 1994).

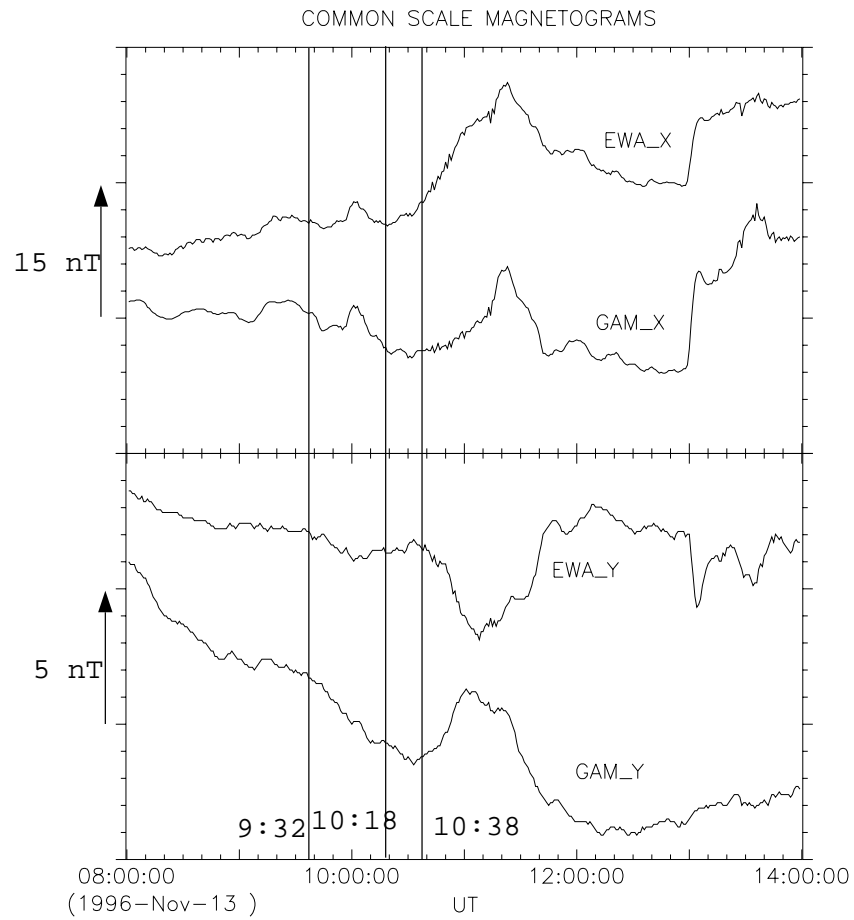


**Plate 1.** Data from the meridional scanning photometer at Poker Flat (location shown in Figure 2). Vertical lines denote a substorm precursor, the onset and a major intensification.

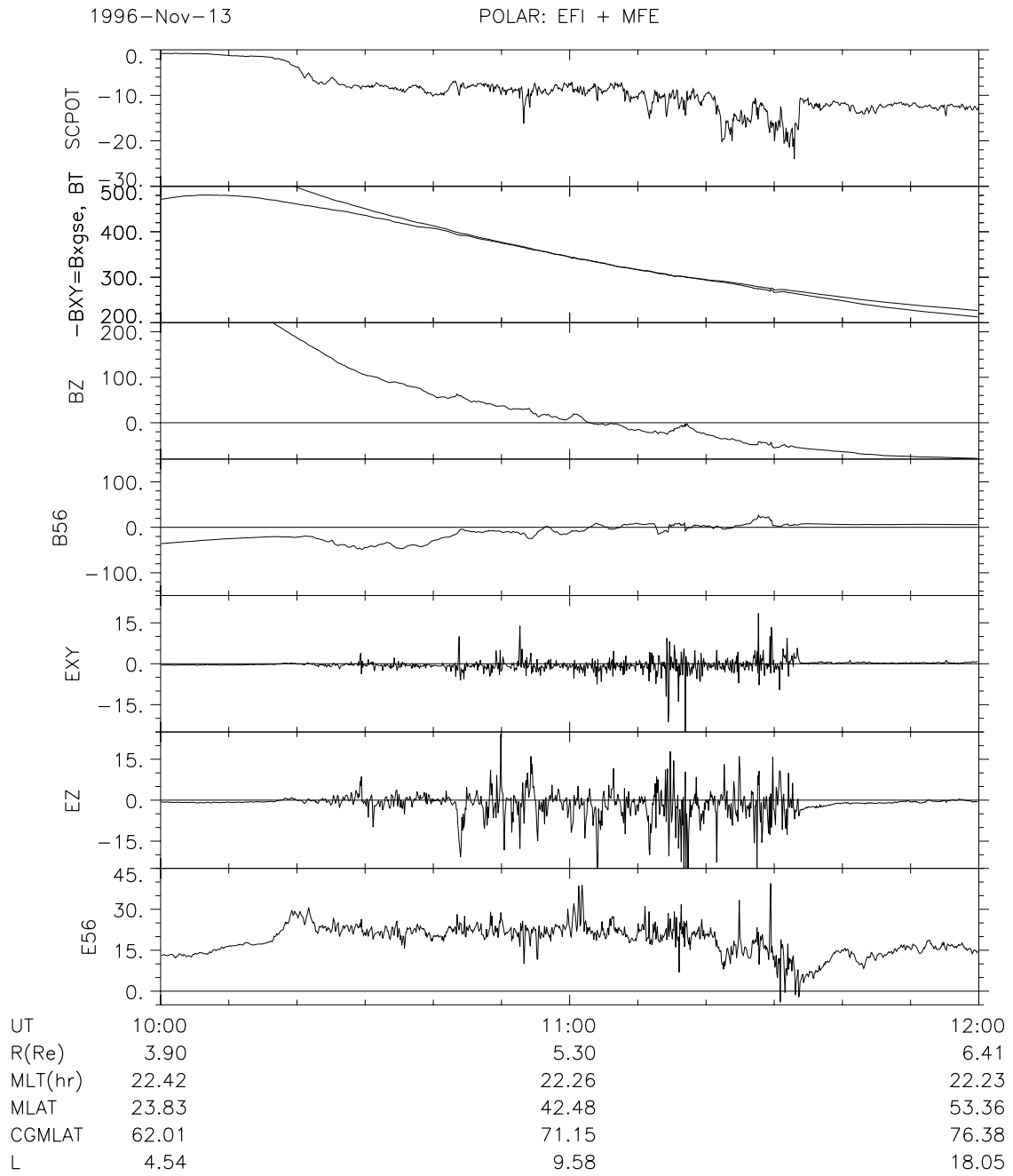


**Figure 3.** Auroral zone common-scale ground magnetograms from stations shown in Figure 2. Each minor tickmark is 100 nT.

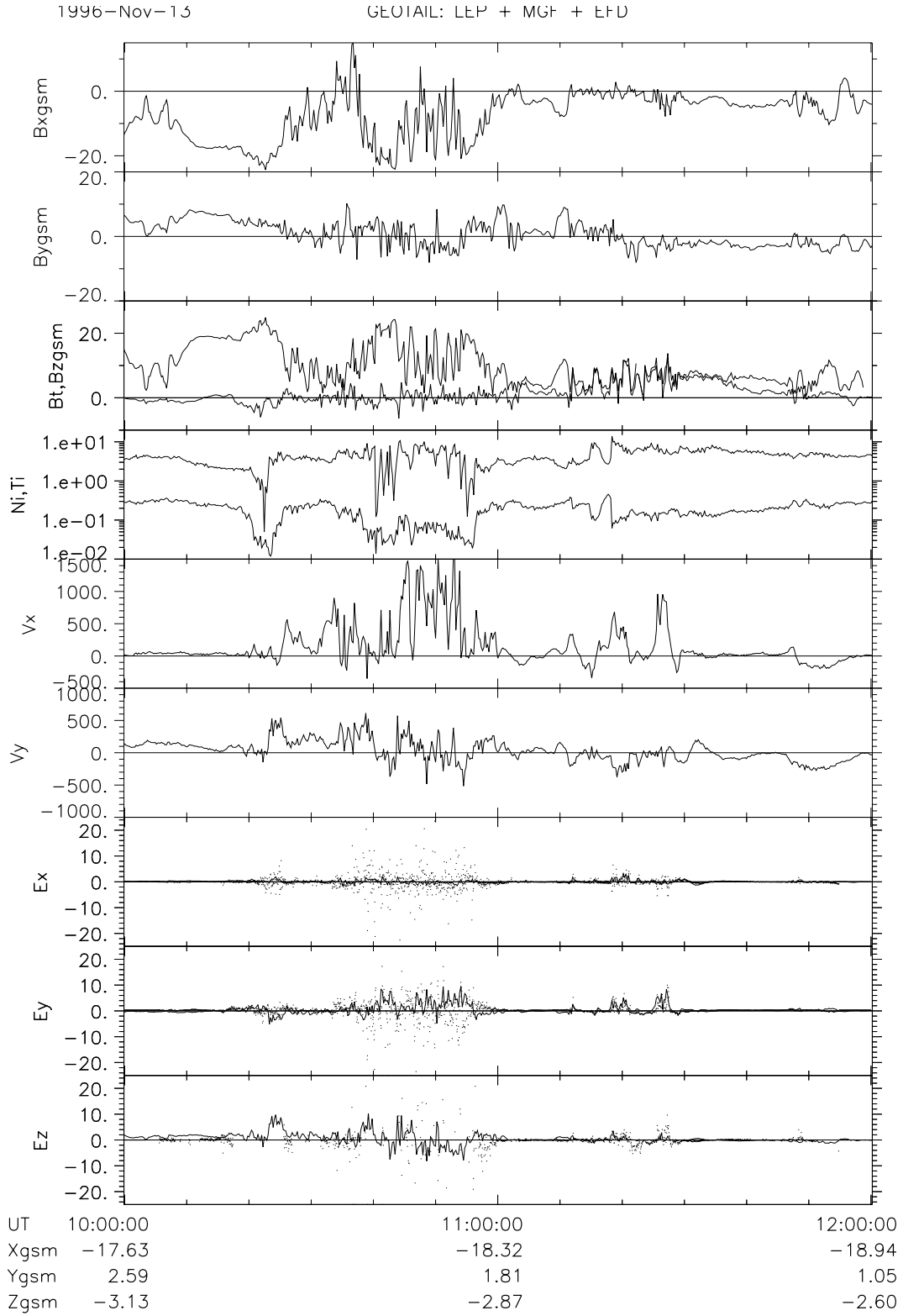




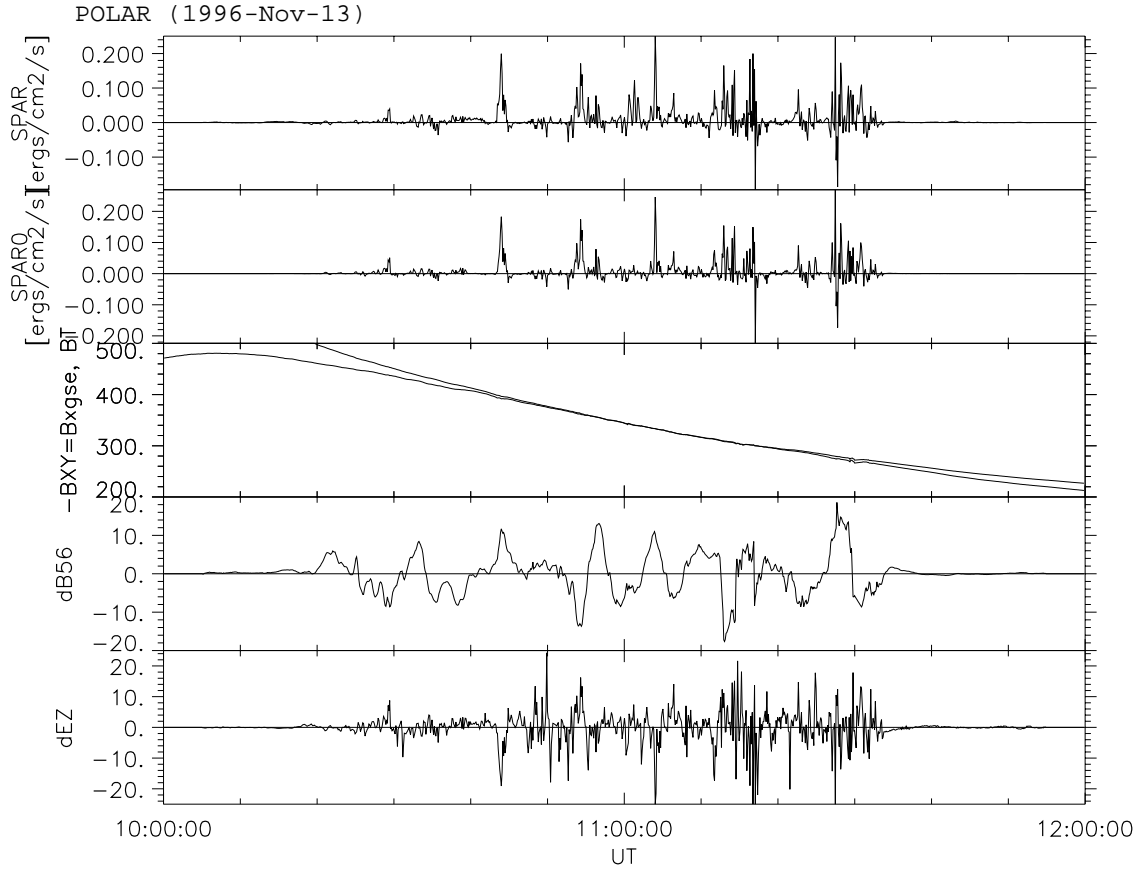
**Figure 4.** Mid-latitude, common-scale ground magnetograms in the north south (X, positive north) and East-West (Y, positive East) directions.



**Figure 5.** Event overview from the POLAR spacecraft at spin-period resolution (6 s).

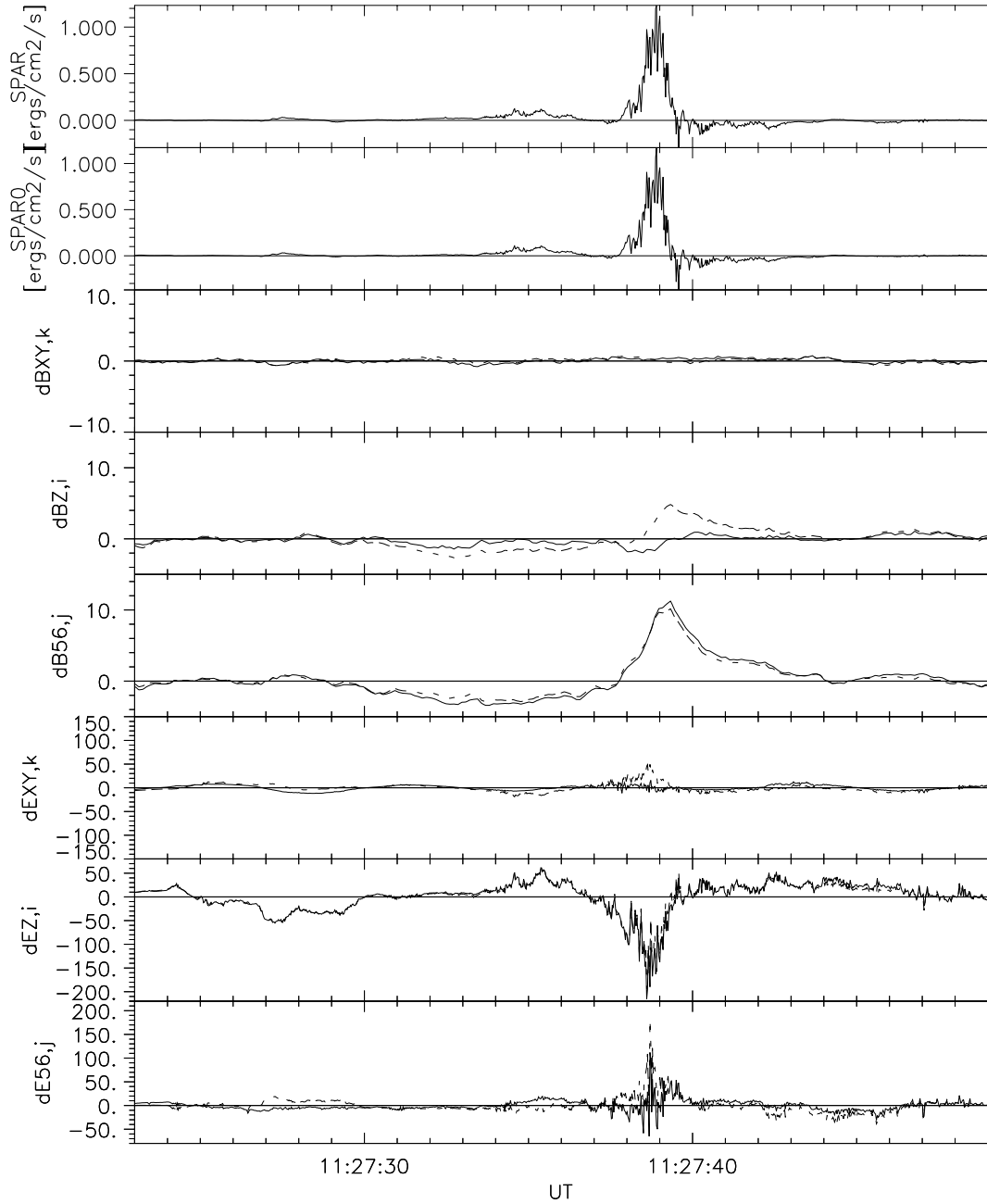


**Figure 6.** Event overview from the Geotail spacecraft. The resolution is 12 s for the magnetic field,  $B$  (nT), and the plasma flow,  $V$  (km/s), density  $N_i$  ( $\text{cm}^3$ ) and temperature  $T_i$  (keV) data and 3 s for the electric field  $E$  (mV/m) data.



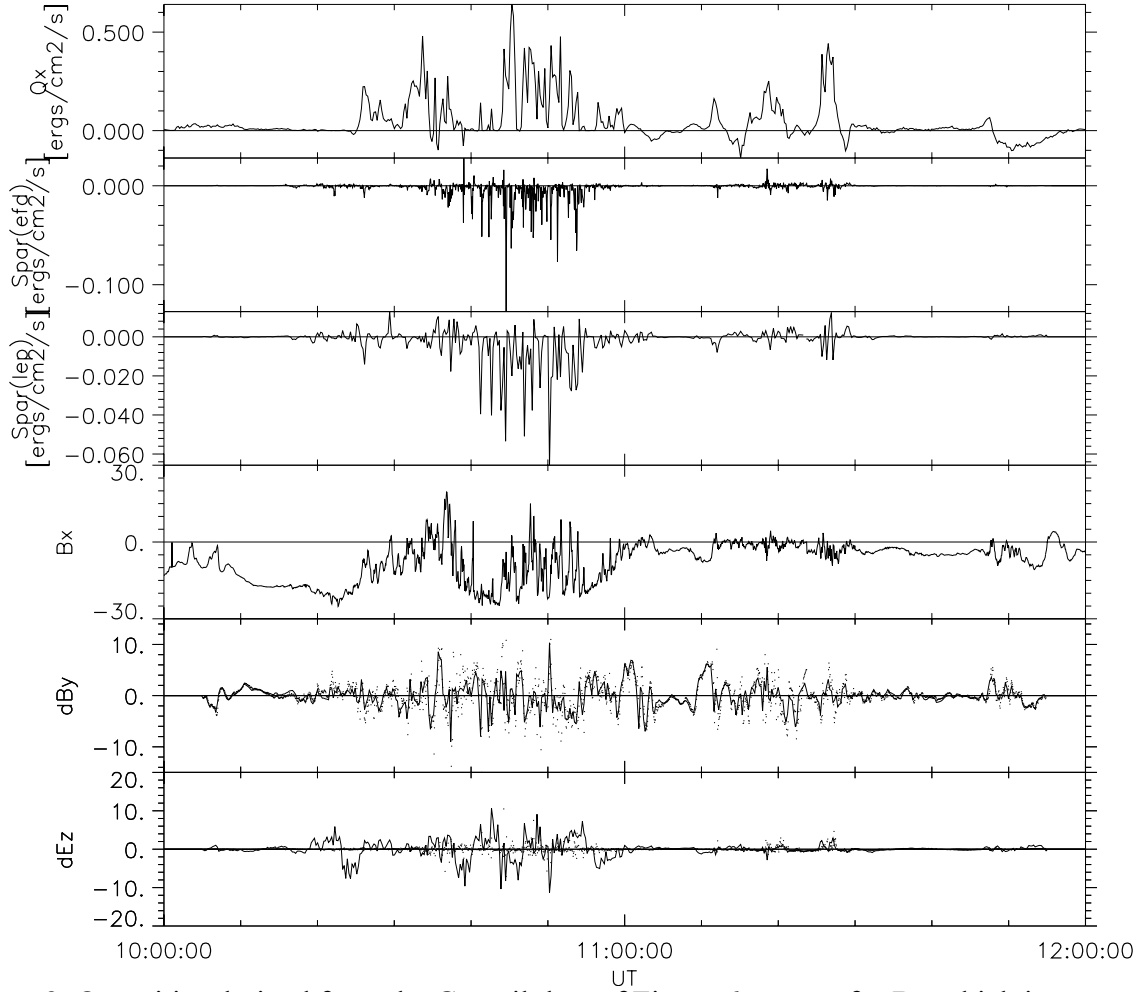
**Figure 7.** Quantities derived from the POLAR data of Figure 5, except for BXY and BT which are same as in Figure 5. dEZ and dB56 are detrended electric and magnetic field data derived from Ez and B56 after subtracting a 10 min running average. SPAR is the Poynting flux computed from such detrended traces of the full  $\mathbf{E}$  and  $\mathbf{B}$  vectors and projected along the instantaneous magnetic field direction. SPAR0 is the Poynting flux computed by using only the spin-plane components of the electric field and assuming  $\mathbf{E} \cdot \mathbf{B} = 0$  to obtain the third component.

POLAR (1996–Nov–13)



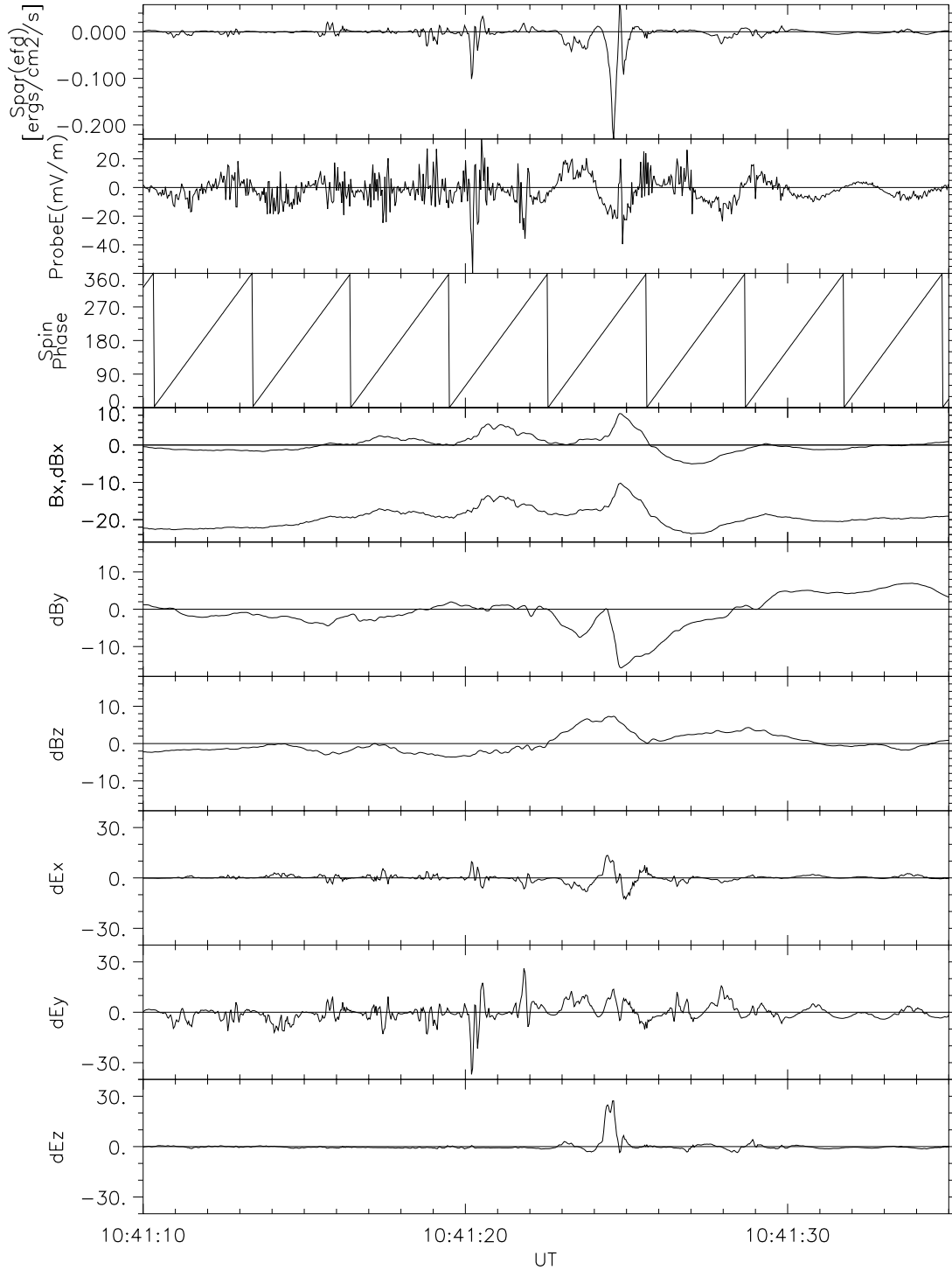
**Figure 8.** SPAR and SPAR0 are the same quantities as in Figure 7, except computed from high time resolution data (0.025s for **E** and 0.12s for **B**). The window used for running average subtraction was 20 sec. Dashed lines represent data in the XY, Z, and 56 coordinate system. Solid lines represent data in the coordinate system “ijk” obtained from minimum variance analysis on the electric field. This is near-identical to the principal axes directions obtained from performing a minimum variance analysis on the magnetic field.

GEOTAIL (1996–Nov–13)

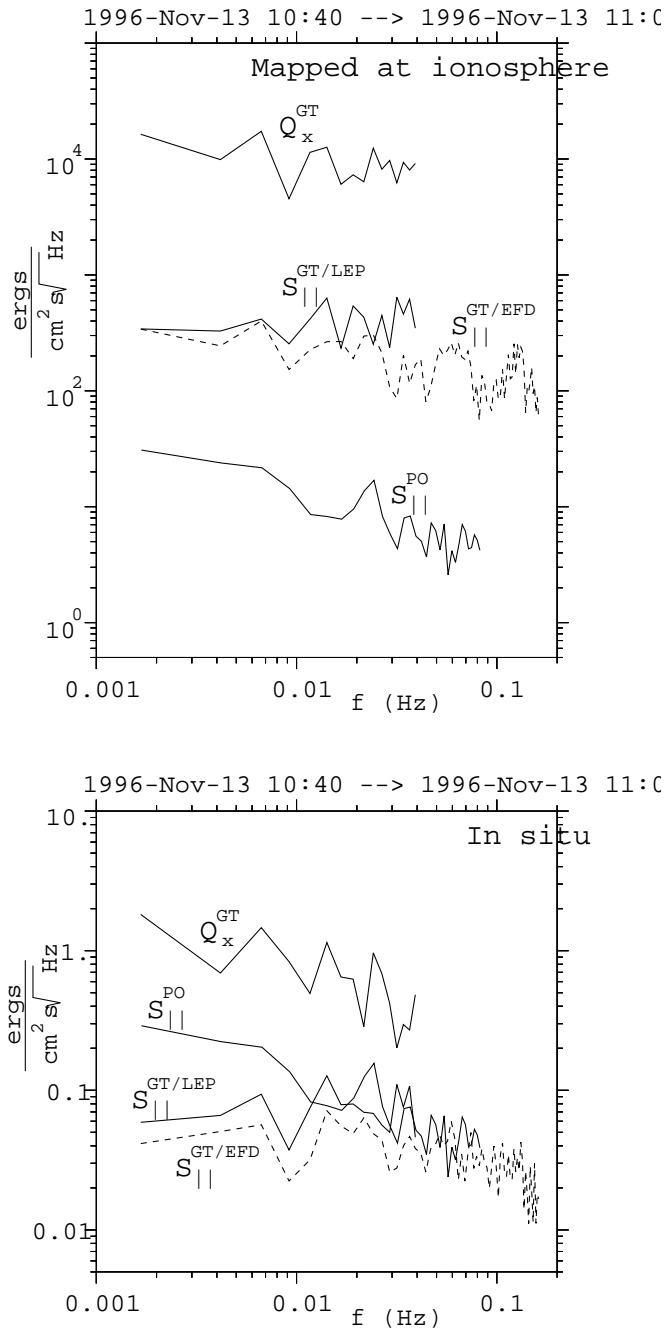


**Figure 9.** Quantities derived from the Geotail data of Figure 6, except for  $B_x$  which is same as in Figure 6.  $dE_z$  and  $dB_y$  are detrended electric and magnetic field data derived from  $E_z$  and  $B_{56}$  after subtracting a 10 min running average.  $S_{par}(lep)$  is the field aligned component of the Poynting flux computed from the full  $\mathbf{E}$  and  $\mathbf{B}$  data, where the electric field was obtained from the measured plasma flow assuming the  $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$  approximation. This is at 12 s resolution.  $S_{par}(efd)$  is the Poynting flux computed from the electric field measured by the EFD instrument assuming  $E_z = 0$ , at 3s resolution. It is an underestimate of the actual value of  $S_{par}$ .  $Q_x$  is the Earthward MHD energy flux computed at 12s resolution from plasma and magnetic field data.

GEOTAIL (1996–Nov–13)

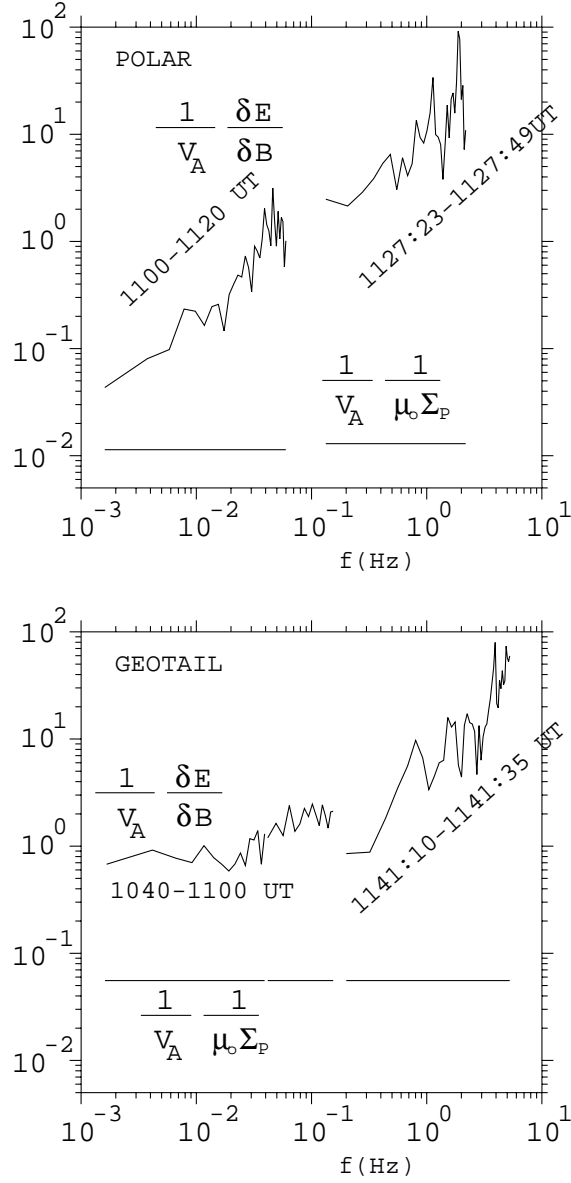


**Figure 10.** High time resolution electric and magnetic field data from Geotail. Spar is the parallel Poynting flux. ProbeE is the instantaneous measurement of the electric field along the double-probe boom direction. The spin phase angle is shown also. The Ez electric field component is formed, under favorable magnetic field orientations, by projecting the ProbeE measurement along the X and Y directions and using the  $E \cdot B = 0$  approximation.

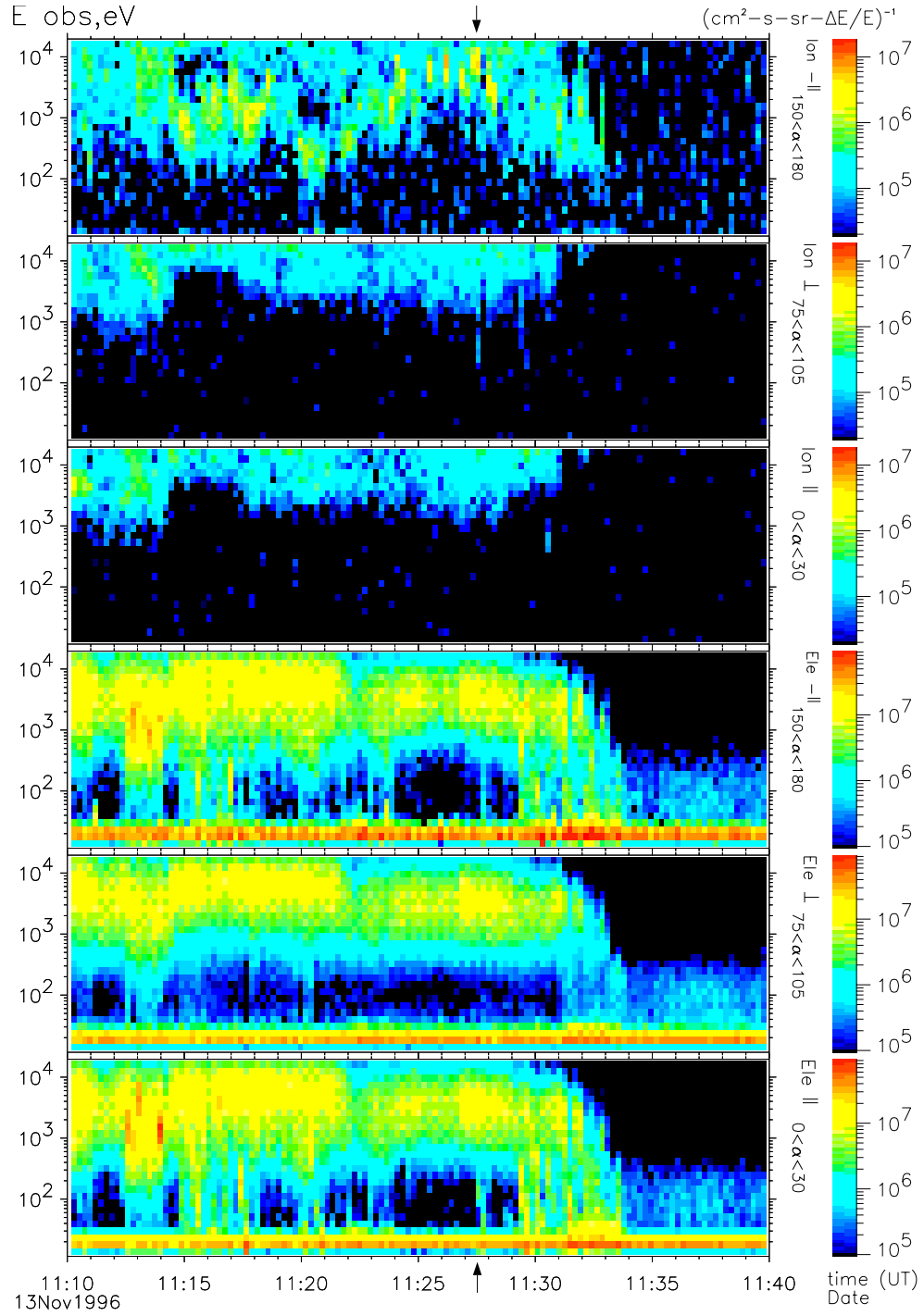


**Figure 11.** Spectral density of Poynting flux on POLAR and Geotail, and energy flux on Geotail. Bottom: In situ measurements. Top: Mapped at 100 km altitude.

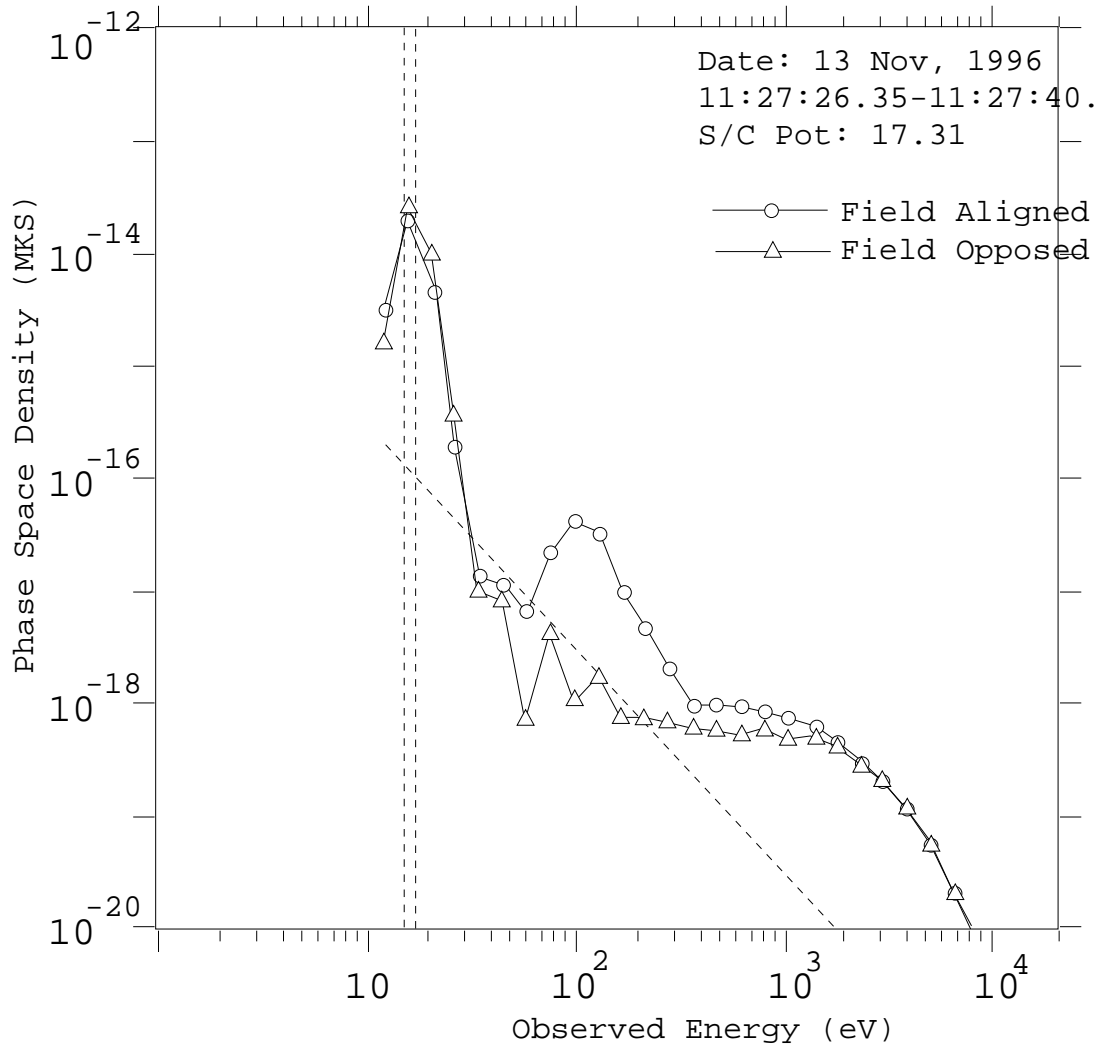




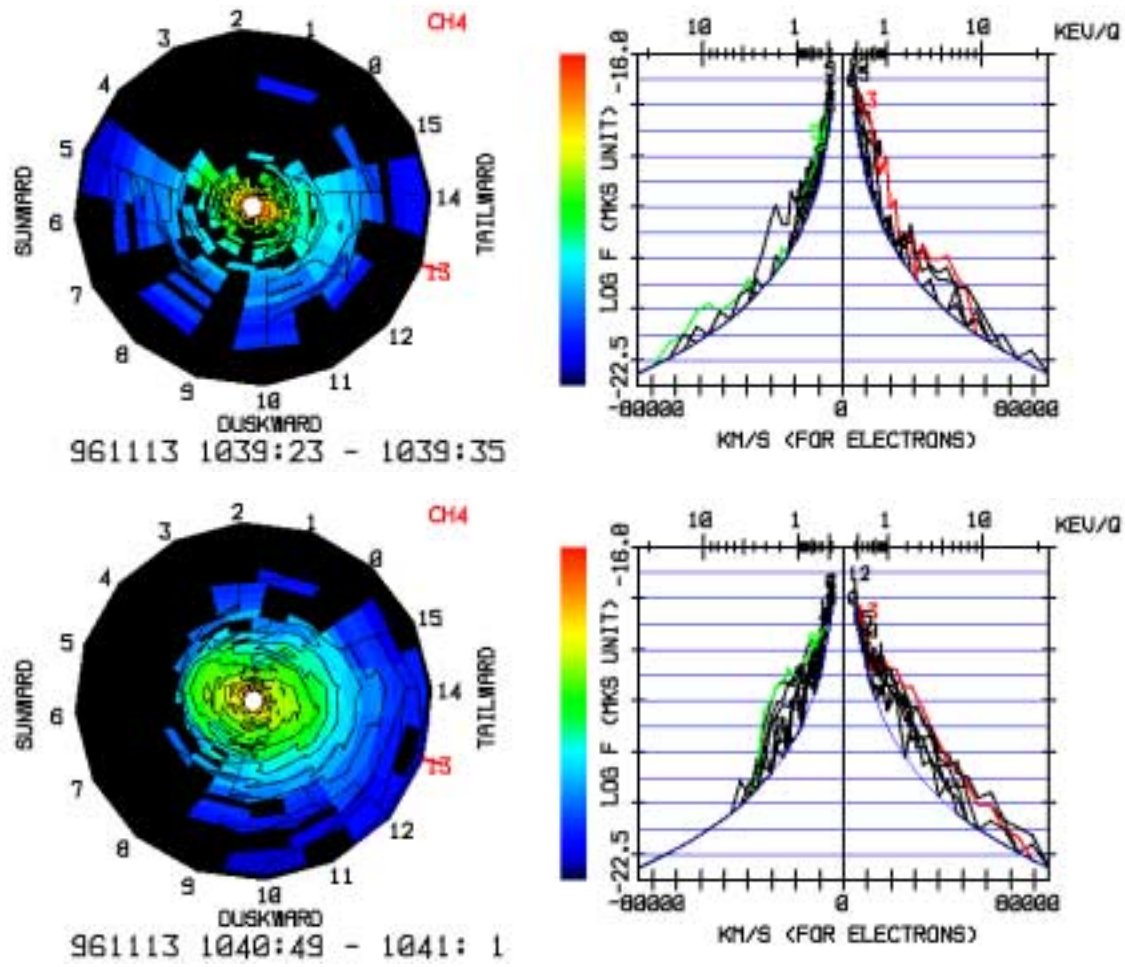
**Figure 12.** E-to-B ratios normalized to the local Alfvén velocity and plotted as a function of frequency. Also shown are the values of inverse of a nominal height integrated Pedersen conductivity of  $\Sigma_P=10$  mhos.



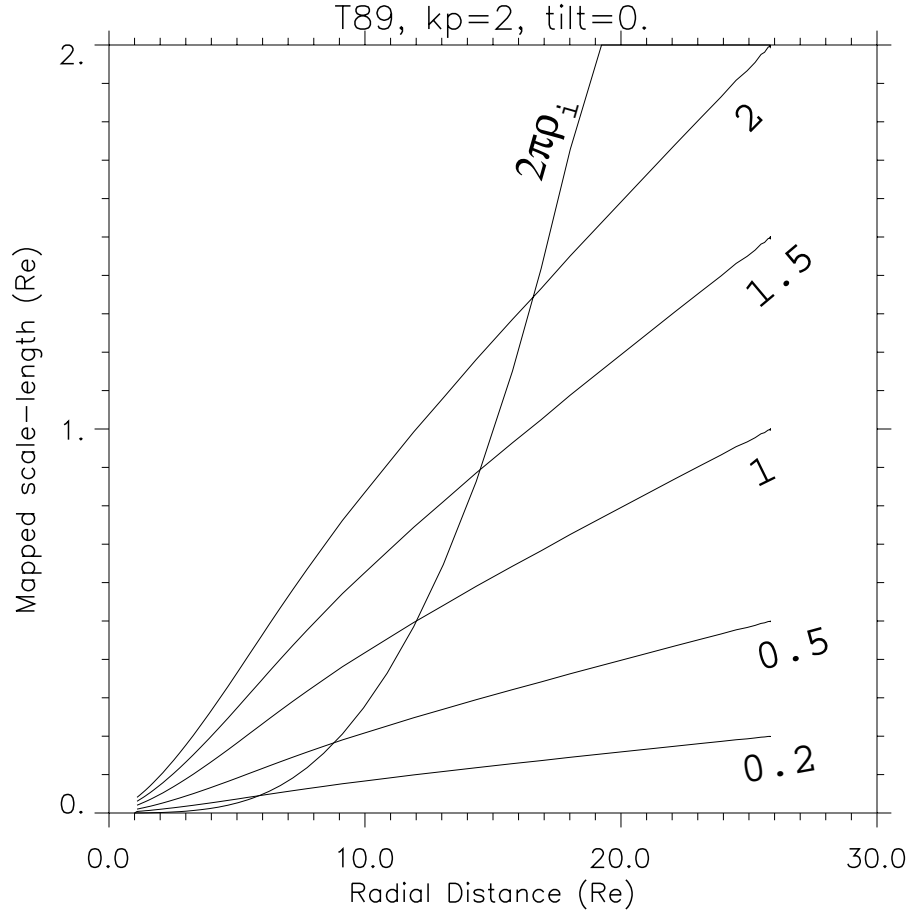
**Plate 2.** Ion and electron energy flux spectrograms from the HYDRA instrument on the POLAR satellite. The arrows mark the times of the peak Poynting flux observation. The data are arranged in pitch angle ranges of 0-30, 75-105 and 150-180 degrees, as indicated next to the color bars. The top 3 panels are electrons and the bottom three are ions.



**Figure 13.** Cuts through the parallel and anti-parallel electron distributions in units of phase space density ( $\text{s}^3/\text{m}^6$ ) at the time of observation of the large Poynting flux spike on POLAR, demarkated by the arrows in Plate 2.



**Plate 3.** Electron distributions from the LEP instrument on the Geotail satellite for two times near the observation of the large Poynting flux spike of Figure 10.



**Figure 14.** Plots of the cross-scale size of a flow-burst mapped along a realistic magnetic field model (T89) from the equatorial magnetotail down to the ionosphere. Different values denote a different starting spatial scale in units of  $R_E$ . Also shown is the quantity  $2\pi\rho_i$ , assuming a constant ion temperature of  $4\text{keV}$  and density of  $0.3\text{cm}^{-3}$ . At a given radial distance kinetic effects start becoming important when  $2\pi\rho_i/d \geq 0.2$ , where  $d$  is the mapped flow burst size. For a  $1R_E$  equatorial cross-tail size flow burst, this corresponds to an altitude of  $6 R_E$ .